AD-A112 321 FUGRO NATIONAL INC. LONG BEACH CA F/G 8/5

MX SITING INVESTIGATION GRAVITY SURVEY - WHIRLWIND VALLEY, UTAH--ETC(U)

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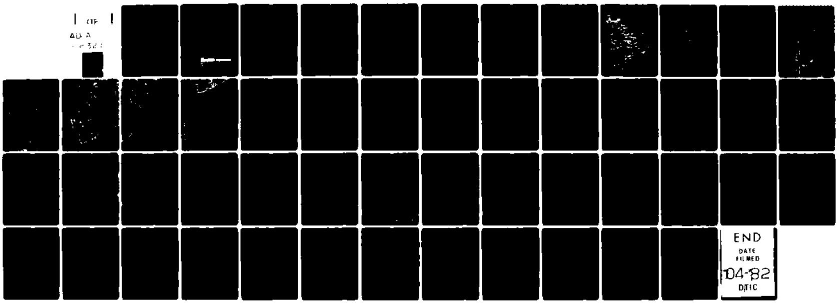

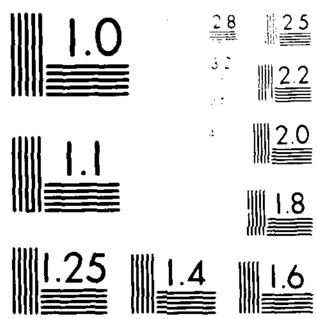
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MX SITING INVESTIGATION

GRAVITY SURVEY - WHIRLWIND VALLEY

UTAH

Prepared for:

U.S. Department of the Air Force
Ballistic Missile Office (BMO)
Norton Air Force Base, California 92409

Prepared by:

Fugro National, Inc.
3777 Long Beach Boulevard
Long Beach, California 90807

30 January 1980

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER FN-TR-33-WW ~~FN-TR-33-WW~~	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) MX Siting Investigation Gravity Survey - Whirlwind Valley NV		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER FN-TR-33-WW
7. AUTHOR(*s*) Fugro National		8. CONTRACT OR GRANT NUMBER(*s*) F04704-80-C-0006
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ertec Western Inc. (formerly Fugro National) P.O. Box 7765 Long Beach Ca 90807		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 64312 F
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Department of the Air Force Space and Missile Systems Organization Norton AFB Ca 92409 (SAMSO)		12. REPORT DATE 30 Jan 80
		13. NUMBER OF PAGES ~~E~~ 25
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) --
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

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17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Gravity [redacted] Survey, Geology, Bouguer Anomaly, Depth to Rock, Valley Fill, Faults, Gravity Profile, Graben

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Gravity measurements were made in Whirlwind Valley for the purpose of estimating the overall shape of the structural basin & the thickness of alluvial fill in the basin. The estimates will be useful in modeling the dynamic response of the basin to explosive or earthquake-generated ground motion and in evaluating ground-water resources.

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FOREWORD

Methodology and Characterization Studies during fiscal years 1977 and 1978 included gravity surveys in ten valleys in Arizona (five), Nevada (two), New Mexico (two), and California (one). The gravity data were obtained for the purpose of estimating the gross structure and shape of the basins and the thickness of the valley fill. There was also the possibility of detecting shallow rock in areas between boring locations. Generalized interpretations from these surveys were included in Fugro National's Characterization Reports (FN-TR-26a through e).

During the FY 77 surveys, the measurements were made to form an approximate one-mile grid over the study areas, and contour maps showing interpreted depth to bedrock were made. In FY 79, the decision was made to concentrate the available funds on the basic Verification Program to verify and refine suitable area boundaries. This decision resulted in a reduction in the gravity program. Instead of obtaining gravity data on a grid, the reduced program consisted of obtaining gravity measurements along profiles across the valleys where Verification Studies were also performed.

The Defense Mapping Agency (DMA), St. Louis, was also requested to provide gravity data from their library to supplement the gravity profiles. For Big Smoky, Reveille, and Railroad valleys, a sufficient density of library data is available to permit construction of interpreted contour maps instead of two-dimensional cross sections.

In late summer of FY 79, supplementary funds became available to begin data reduction. At this time, inner zone terrain corrections began on the library data and the profiles from Big Smoky Valley, Nevada, and Butler and La Posa valleys, Arizona. The profile data from Whirlwind, Hamlin, Snake East, White River and Garden Coal valleys, Nevada were available from the field in early October, 1979.

A continuation of gravity interpretations has been incorporated into the FY 80 contract and the results are being summarized in a series of valley reports. The reports covering Nevada-Utah gravity studies will be numbered, "FN-TR-33-", followed by the abbreviation for the subject valley. In addition, more detailed reports of the results of FY 77 surveys in Dry Lake and Ralston valleys, Nevada are being prepared. Verification Studies are continuing in FY 80 and gravity studies are included in the program. DMA will continue to obtain the field measurements and it is planned to return to the grid pattern. The interpretation of the grid data will allow the production of contour maps which will be valuable in the deep basin structural analysis needed for computer modeling in the Water Resources Program. The gravity interpretations will also be useful in the Nuclear Hardness and Survivability (NH&S) evaluations.

The basic decisions governing the gravity program are made by BMO following consultation with TRW Inc., Fugro National and the (DMA). Conduct of the gravity studies is a joint effort between DMA and Fugro National. The field work, including planning, logistics, surveying, and meter operation is done by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), headquartered in Cheyenne, Wyoming. DMAHTC reduces the data to Simple Bouguer Anomaly (see Section A1.4, Appendix A1.0). The Defense Mapping Agency Aerospace Center (DMAAC), St. Louis, calculates outer zone terrain corrections.

Fugro National provides DMA with schedules showing the valleys with the highest priorities. Fugro National also recommended locations for the profiles in the FY 79 studies within the constraints that they should follow existing roads or trails. Any required inner zone terrain corrections are calculated by Fugro National prior to making geologic interpretations.

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1.0 INTRODUCTION

1.1 OBJECTIVE

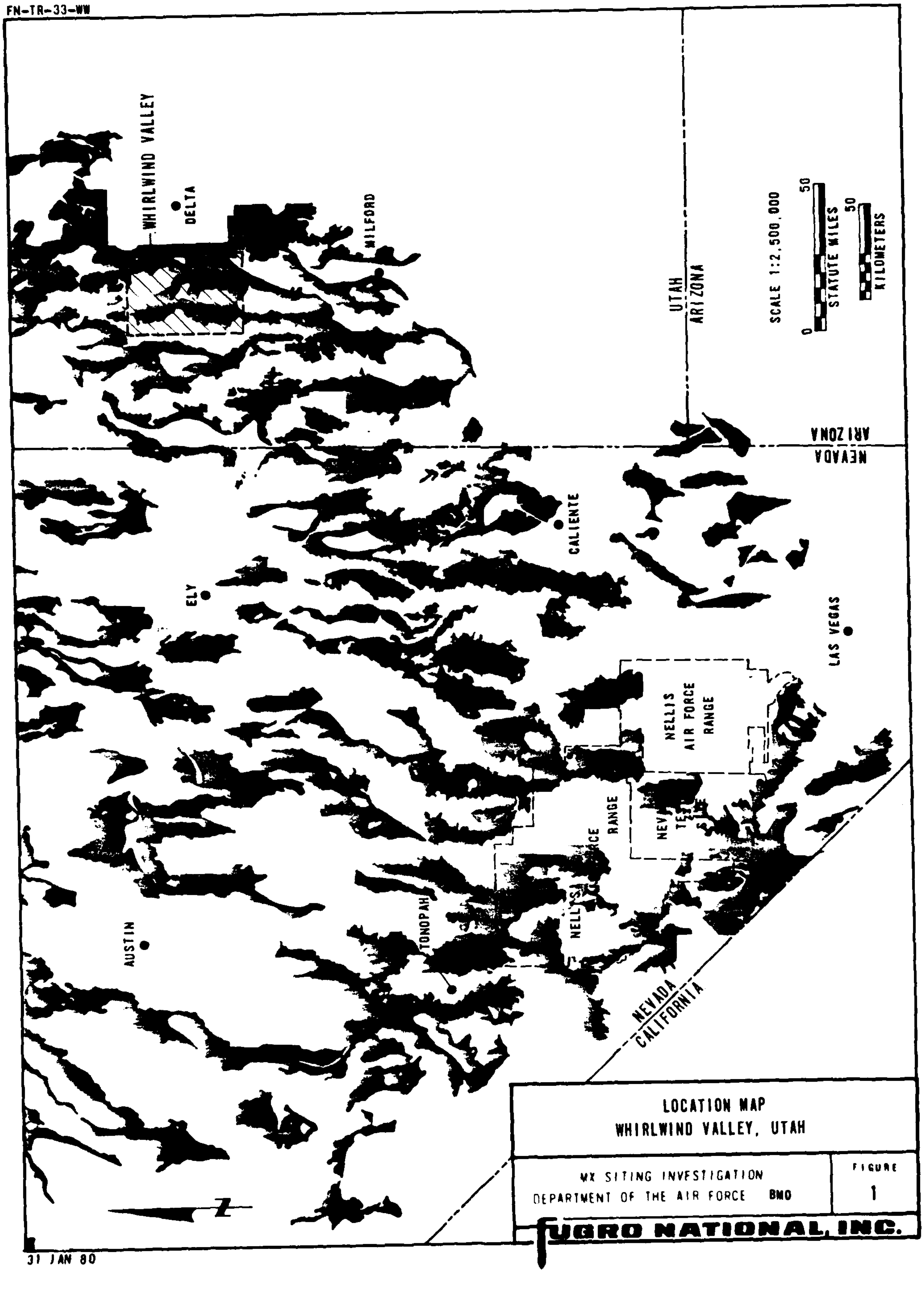
Gravity measurements were made in Whirlwind Valley for the purpose of estimating the overall shape of the structural basin and the thickness of alluvial fill in the basin. The estimates will be useful in modeling the dynamic response of the basin to explosive or earthquake-generated ground motion and in evaluating ground-water resources.

1.2 LOCATION

Whirlwind Valley is located in western Millard and western Juab counties, Utah about 30 miles (48 km) west of the town of Delta (Figure 1). The valley is bounded on the east by the Little Drum Mountains and on the west by the House Range (Figure 2). It culminates northward in Swasey Bottom near the Juab County line, and is open southeastward toward Lake Sevier and the Sevier Desert. U.S. Highway 6/50 crosses the southern end of the valley.

1.3 SCOPE OF STUDY

The Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) made gravity measurements along five cross-valley profiles as illustrated in Figure 2. The distance between the profiles ranged from 5 to 8 miles (8 to 13 km) between the profiles. The sampling interval was 1 mile (1.6 km) over the central valley and 1/4 mile (0.4 km) near the valley margins. The more dense sampling was used near the valley margins to define any gradients associated with boundary faults and to



LOCATION MAP
WHIRLWIND VALLEY, UTAH

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FIGURE
1

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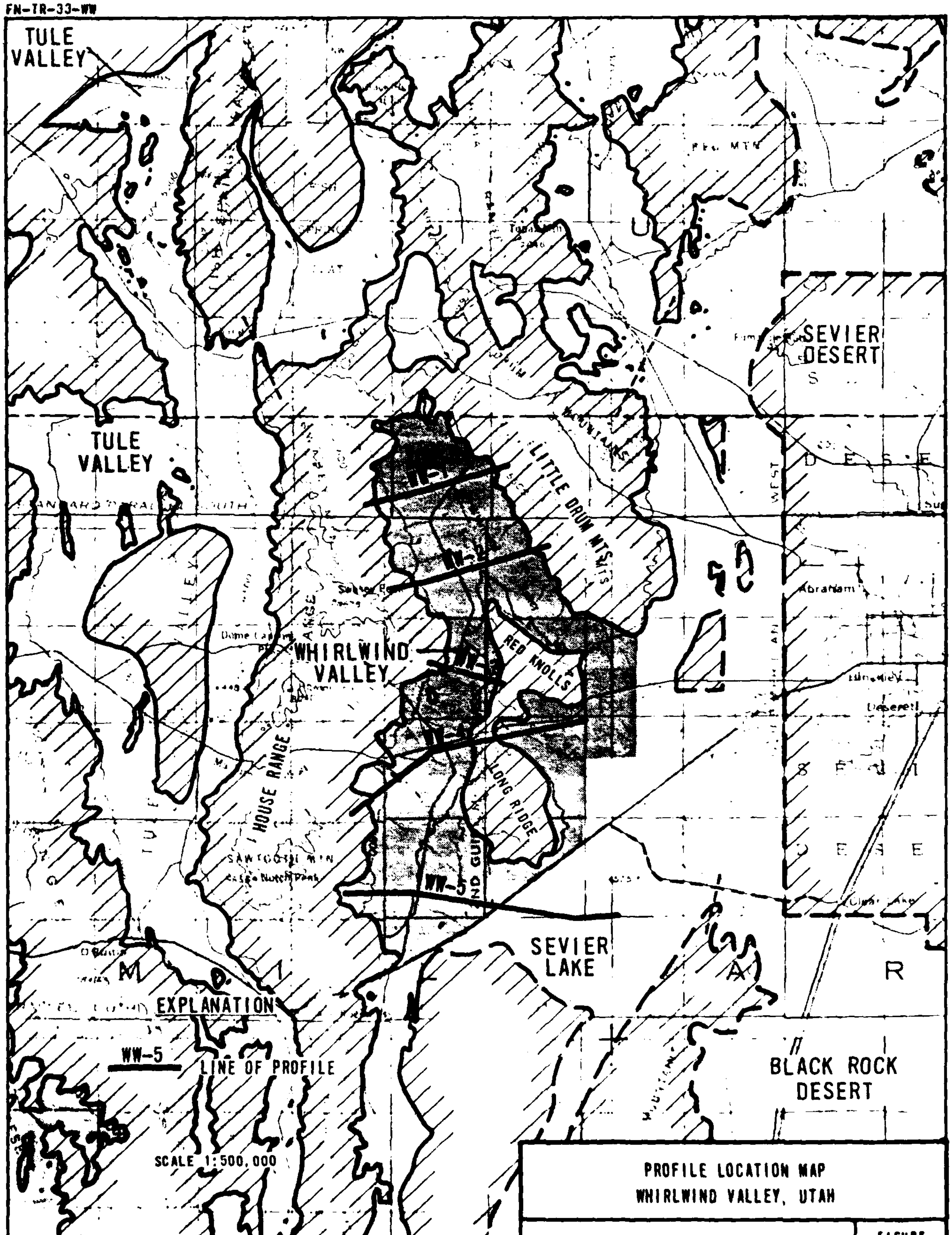

PROFILE LOCATION MAP
WHIRLWIND VALLEY, UTAH

MX SITING INVESTIGATION DEPARTMENT OF THE AIR FORCE - BMO	FIGURE 2

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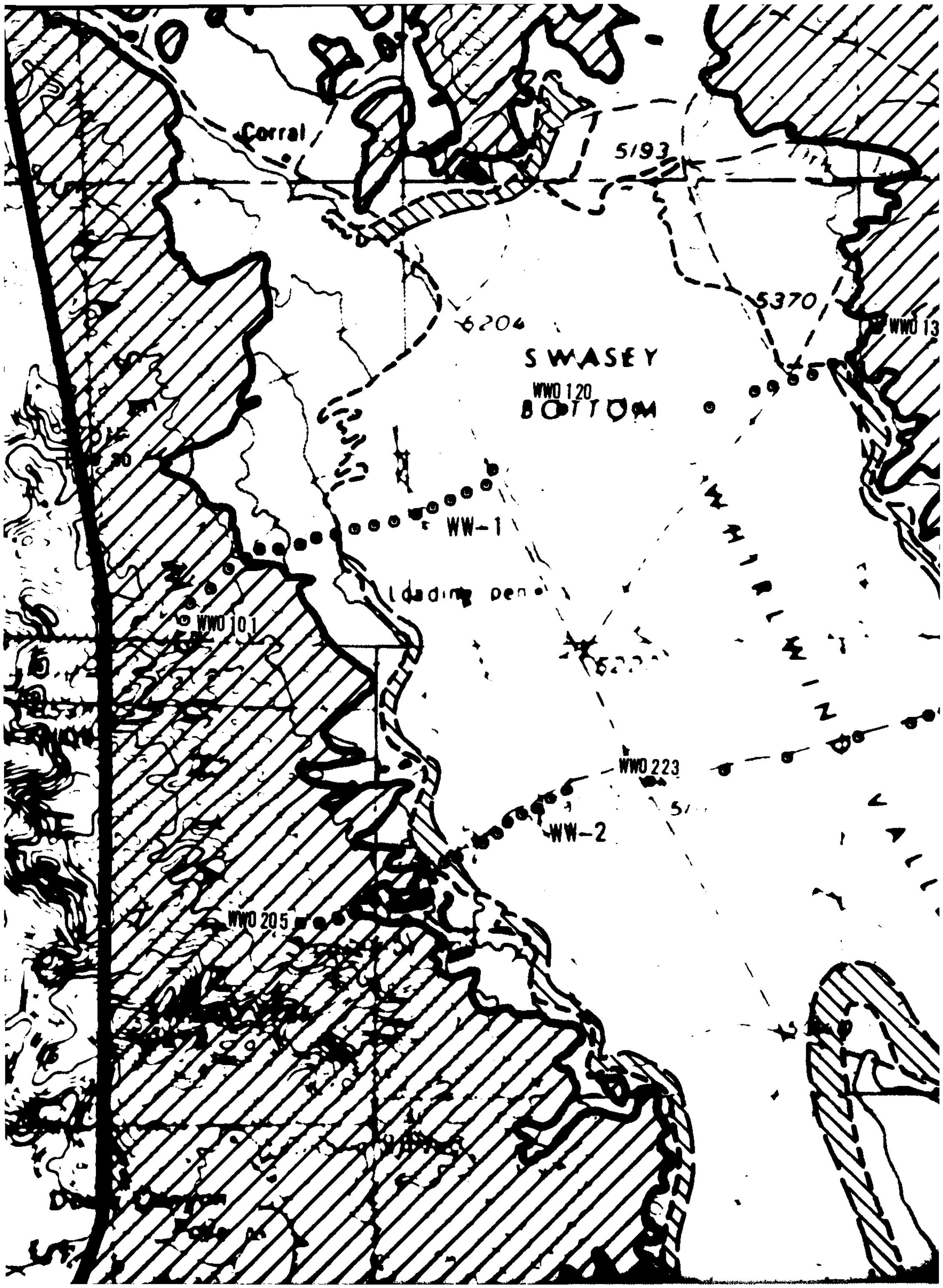
31 JAN 80

identify short-wavelegth anomalies which might occur if bedrock was shallow along the margins of the valley. The station locations are shown in Figure 3 and the station data are listed in Appendix A2.0. The tolerance for establishing station elevations was 5 feet (1.5 m). This tolerance for elevation control limited the gravity precision to 0.3 milligals.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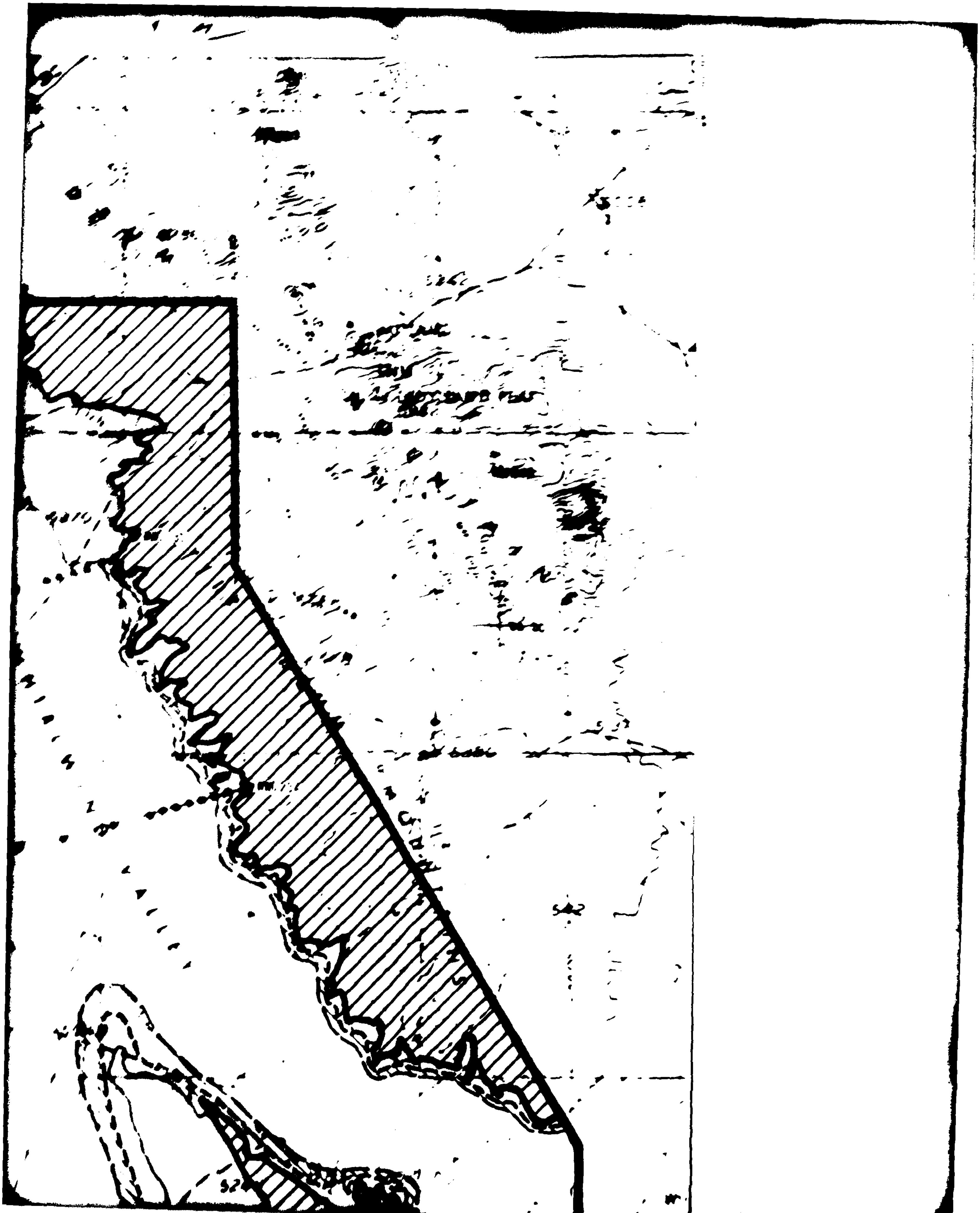
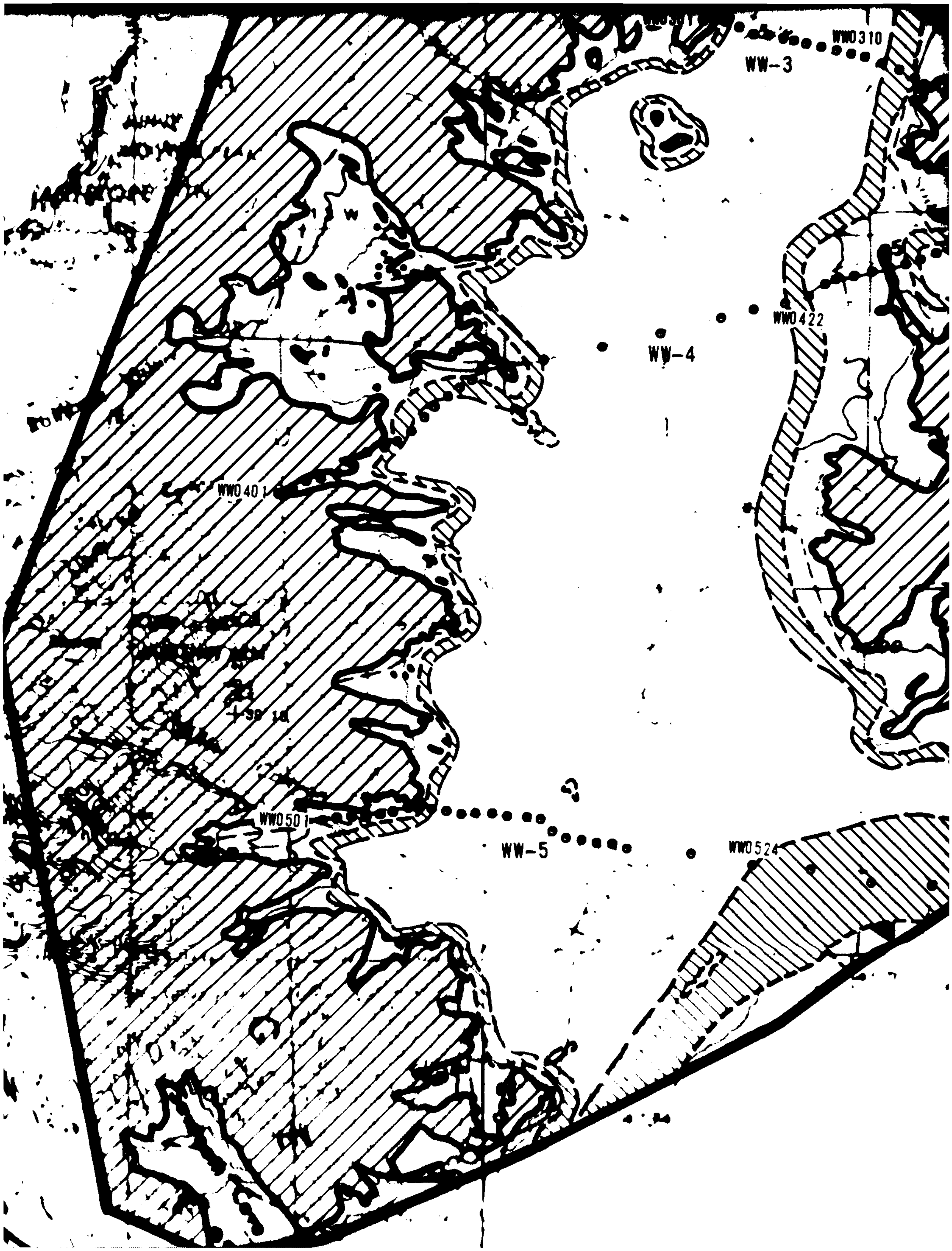
SWASEY
BOTTOM
WWO 120
WWO 13
WW-1
loading pen
WWO 101
WWO 223
WW-2
WWO 205

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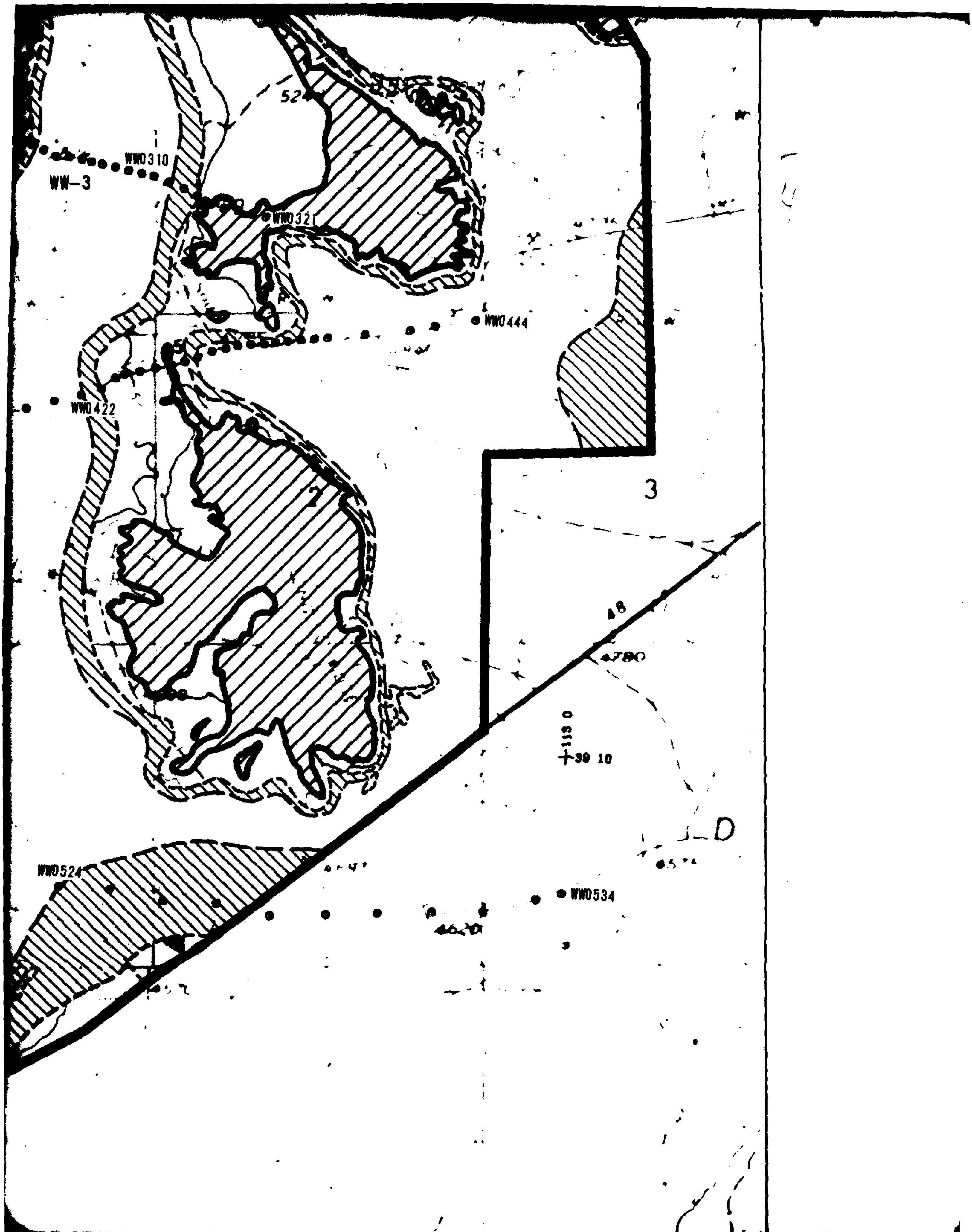
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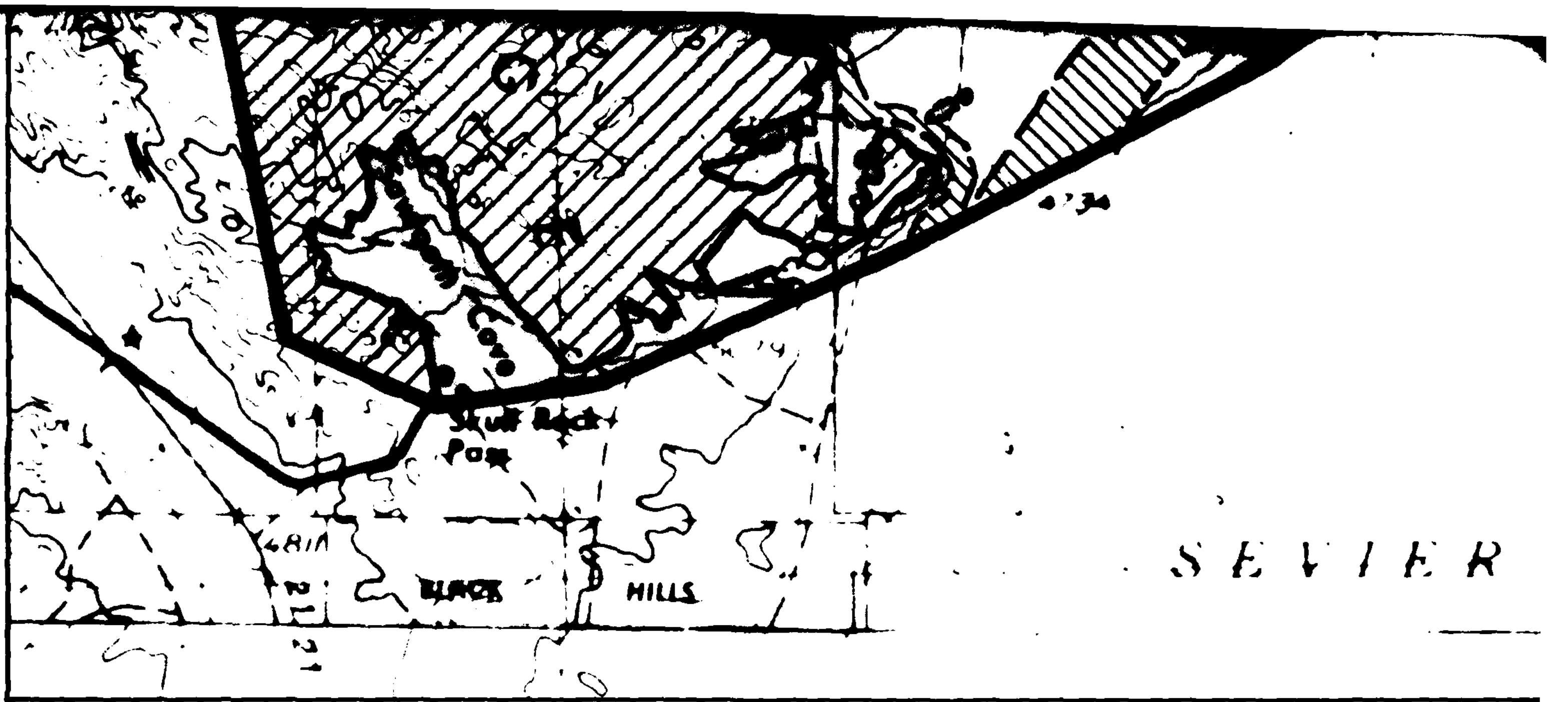

EXPLANATION

WW0310 Gravity station number

○○○ Gravity station location

WW–1 Profile name

Area suitable for hybrid trench and vertical shelter basing modes. Depth to rock and water greater than 150 feet (46m).

Area suitable for hybrid trench and not suitable for vertical shelter. Depth to rock and water greater than 50 feet (15m) and less than 150 feet (46m).

Area unsuitable for both hybrid trench and vertical shelter basing modes as determined from application of depth to rock and water, topographic, terrain, and cultural exclusions. (See Section A2.0 in Appendix for details of exclusion criteria)

Indicates areas of exposed rock.

Contact between rock and basin fill.

Whirlwind verification site boundary, FY 79

GRAVITY STATION LOCATION MAP
WHIRLWIND VALLEY, UTAH

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FIGURE 3

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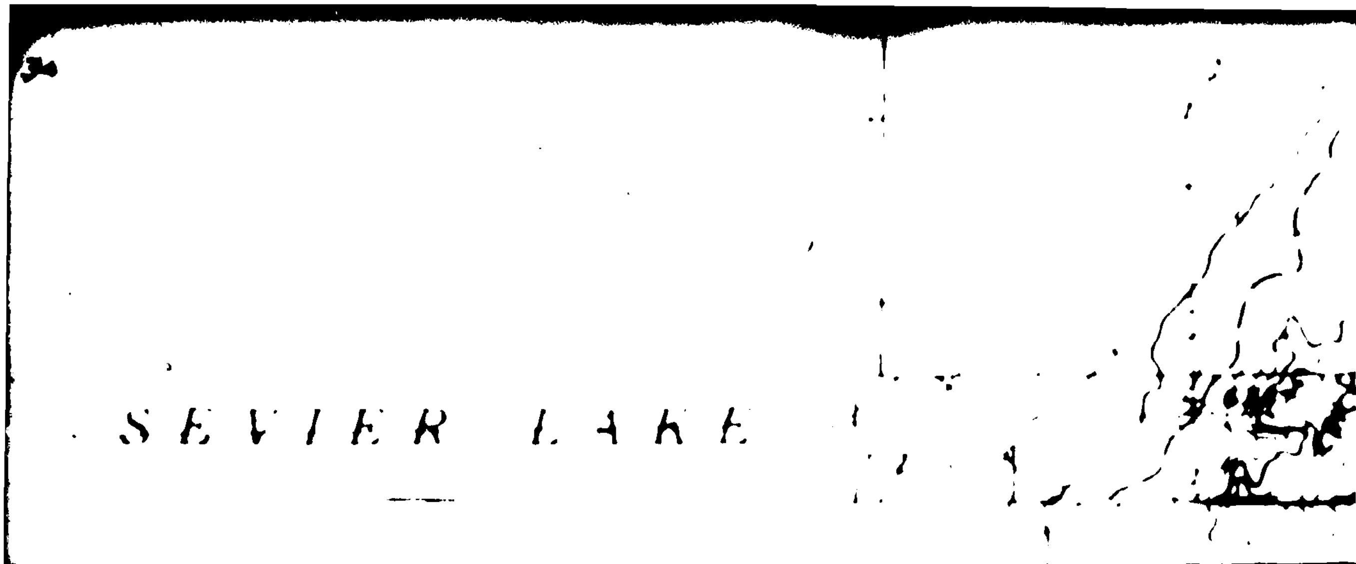

TION

trench and vertical shelter
rock and water greater than

trench and not suitable for
h to rock and water greater
less than 150 feet (46m).

hybrid trench and vertical
determined from application
ter, topographic/terrain, and
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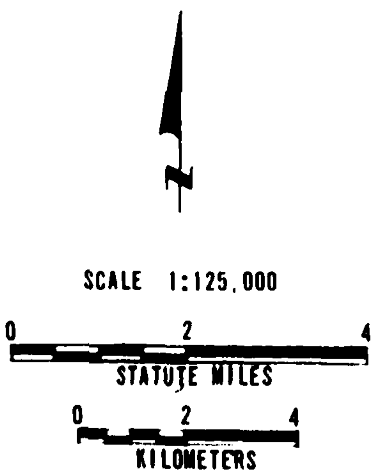
d rock.

basin fill.

te boundary, FY 79



2.0 GRAVITY DATA REDUCTION

DMAHTC obtained the basic observations for each station and reduced them to Simple Bouguer Anomalies (SBA) as described in Appendix A1.0. Up to three levels of terrain corrections were applied to convert the SBA to the Complete Bouguer Anomaly (CBA). First, the Defense Mapping Agency Aerospace Center (DMAAC) used its library of digitized terrain data to calculate corrections for terrain to 104 miles (167 km) from each station. The computation method used has limitations for correcting terrain effects near the stations. This made it necessary to apply a second level of correction for some stations. For these, a ring template was used to calculate the effect of terrain within approximately 3000 feet (914 m) of the station. A third level of terrain correction was applied to those stations where 10 feet or more of relief were observed within 130 feet (40 m) of the station. For these stations, the elevation differences at a distance of 130 feet along six directions from the station were measured in the field. These data were used to calculate the effect of the very near relief.

3.0 GEOLOGIC SUMMARY

Whirlwind Valley lies within the Basin and Range physiographic province. Rocks forming the Little Drum Mountains on the eastern side of the valley consist of early Tertiary volcanic flows (Hintze, 1963; Stokes, 1963). The House Range, which forms the western boundary, contains faulted eastward-dipping limestones and dolomites with interbedded shales of Cambrian age. Ordovician age limestones with interbedded conglomerates crop out south of the valley in the southern House Range west of Sevier Lake. Tertiary age volcanic rocks similar to those in the southern Little Drum Mountains are found along the valley axis in Red Knolls and Long Ridge. Tertiary age conglomerates overlie these volcanic rocks and are the principal units exposed in Long Ridge.

Hintze (1963) and Stokes (1963) suggest only one fault in Whirlwind Valley. They show it concealed by alluvium, trending southeastward into the north-central part of the valley. The House Range to the west is considered by Gehman (1958) to be the gently eastward dipping limb of a faulted anticline. If this is the case, the carbonate rocks exposed in the House Range extend beneath the alluvium in Whirlwind Valley, and presumably underlie the volcanic rocks in the Little Drum Mountains. The steep western face of the House Range, bounding the next valley, represents the eroded fault scarp along which uplift has taken place. Few faults are mapped within the Little Drum Mountains although relations are complex because of the variety of volcanic rock types present.

Surficial basin-fill deposits are described in the Verification Studies (FY 79, FN-TR-27-1A). They are predominantly alluvial fan and lacustrine deposits. The lacustrine deposits are associated with Pleistocene age Lake Bonneville and occur principally in the southern and central parts of the valley. The alluvial deposits consist primarily of silty sand with lesser amounts of gravelly sand, silt, and clay. Younger alluvial fans are generally uncemented; intermediate alluvial fans are weakly cemented; and older alluvial fans are moderately to strongly cemented.

Published values for densities of soil and alluvium generally range between 1.3 and 2.3 g/cm^3, but sometimes attain greater values under compaction (Grant and West, 1965). Limestone densities generally range between 2.3 and 2.8 g/cm^3 with the older formations having the greater densities.

4.0 INTERPRETATION

A valley filled with relatively low-density alluvium will create a negative gravity anomaly. Thus, a graph of gravity across a valley is often U-shaped, low in the middle of the valley where the fill is thickest, and high on the ends where the fill thins and disappears. The basis for interpretation is the CBA profile. The CBA for the five profiles across Whirlwind Valley are shown in the top portion of Figures 4 through 8.

4.1 REGIONAL - RESIDUAL SEPARATION

The CBA contains gravitational field components contributed by geologic conditions which are unrelated to basin fill. These are known as regional effects and must be removed from the CBA to obtain the gravity contributions made by the valley fill. A regional field was established by linear interpolation between the CBA values at bedrock stations on opposite ends of the profiles. Where only one end of a profile was on bedrock, the regional value was assumed to be constant across the valley. This method does not result in true residual values (that is, some regional effects remain) but the error is probably small compared to the large residual anomaly values produced by the valley fill.

The regional trend used for each profile is shown together with the CBA in the top portion of Figures 4 through 8. The difference between the regional and the CBA is the residual gravity anomaly which is attributed to the presence of the alluvial fill

in the valley. The residual for each profile is shown by the crosses (x) in the center portion of Figures 4 through 8.

4.2 DENSITY SELECTION

The construction of a geologic model to account for the residual anomaly requires selection of density values representative of the basin fill and of the underlying basement rock. Detailed density values are not available. Consequently, generalized values were chosen and used for modeling all five of the profiles.

The density value selected to represent basin floor was 2.8 g/cm^3. This value was chosen because the Paleozoic carbonates in the Great Basin are generally reported to be relatively dense. It is assumed that the carbonate rocks forming the House Range extend across Whirlwind Valley beneath the alluvium.

Average in situ densities for basin fill from four borings sampled at 20-foot (6 m) intervals, between 100 and 160 feet (30 to 49 m), ranged from 2.0 to 2.3 g/cm^3. The density value selected to represent the basin fill was 2.3 g/cm^3. This value is near the high end of the densities measured for samples from 160-foot borings drilled during the Verification Studies of Whirlwind Valley (FY 79, FN-TR-27-II). The high end, instead of the average, of the measured values was used because all the basin fill samples came from relatively shallow depths and densities of alluvial materials usually increase with depth. If compaction at depth has caused the overall effective density to

be greater than $2.3\ g/cm^3$. The thicknesses of alluvium given by the models in Figures 4 through 8 are less than the actual thicknesses.

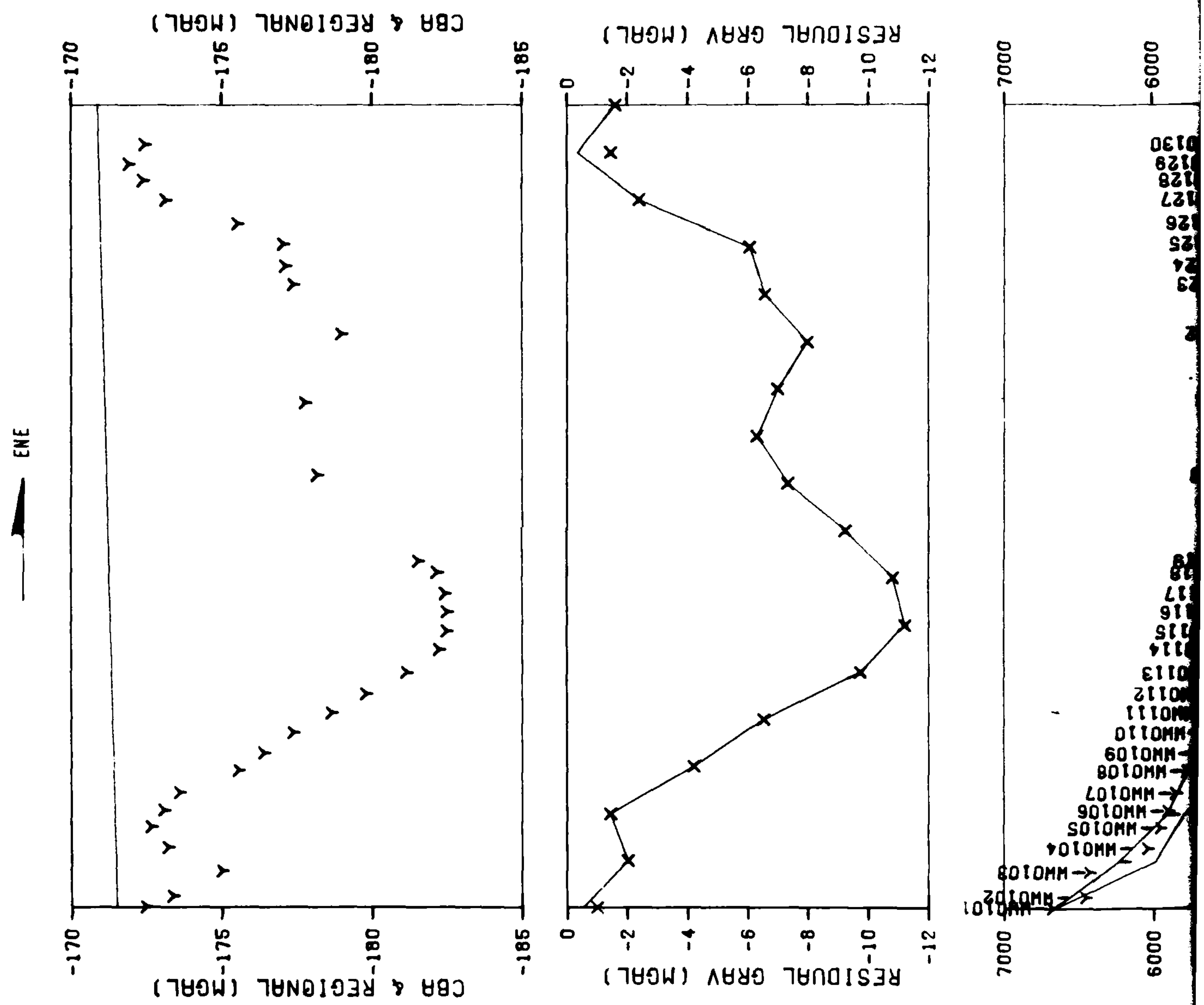
4.3 MODELING

Modeling of the cross-sections of the basin beneath the gravity profiles was done using a two-dimensional computer-modeling program. The model chosen for this analysis appears in cross-section as a set of 1-km-wide blocks whose top is at surface elevation and whose bottom represents the alluvium-bedrock boundary. The elevations at the bottoms of the blocks were adjusted by iterative computation until the computed gravity anomaly for the model differed by less than 1/2 milligal from the observed residual gravity anomaly. The computed gravity anomaly from the final model is shown as a continuous line in the center portion of Figures 4 through 8. The resulting depth-to-bedrock models are shown in the lowest section of Figures 4 through 8.

The shapes of the basement surfaces derived from this modeling have a basin-like character with few complications. Profile 1, on the north (Figure 4), however does show some basement irregularities which may indicate fault blocks or intrusives. The concealed fault suggested by Stokes (1963) ends at about the location of Profile 1. Although presumably the downthrown side would be on the east, the gravity profile shows thinner fill on the east rather than thicker. The figures have a vertical exaggeration of 125/12 times (10.4); therefore, the gentle slopes appear steep.

Proceeding southward, Profile 2 (Figure 5) shows a smooth basin shape. Profile 3 (Figure 6) shows half a basin. Red Knolls, which lies at the eastern end of Profile 3, has little or no gravity expression. Consequently, it is interpreted to be a thin layer of volcanic flow material overlying the basin fill. Profile 4 (Figure 7), also shows the basin floor to be deepest under the western Red Knolls, becoming shallower toward the south end of the knolls. The gravity profile also appears to be unaffected by Long Ridge, two miles to the south. These two profiles indicate that neither the Red Knolls volcanics nor the Long Ridge conglomerates are significantly more dense than the other basin fill, and that they do not lay directly on bedrock. Profile 5 (Figure 8), which passes within a mile of Sevier Lake, shows a bedrock high between the lake and Long Ridge. The calculated bedrock depth is about 240 feet (73 m). This high point may be a structural divide between Whirlwind Valley and the Sevier Desert Basin.

Figures 4 through 8 show that the valley fill thickens by about 400 feet to 500 feet (122 to 152 m) per kilometer outward from bedrock. The greatest depth of fill, about 2000 feet (610 m), is beneath Profile 1. However a more typical depth is about 1000 feet (305 m). These calculated depths are very dependent upon the choice of densities; for example, a one percent increase of assumed fill density for the model makes a five percent decrease in the density contrast and, therefore, a five percent increase in the calculated thickness of fill.


CBA & REGIONAL (MGAL)
RESIDUAL GRAV (MGAL)
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MM0102
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MM0104
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MM0106
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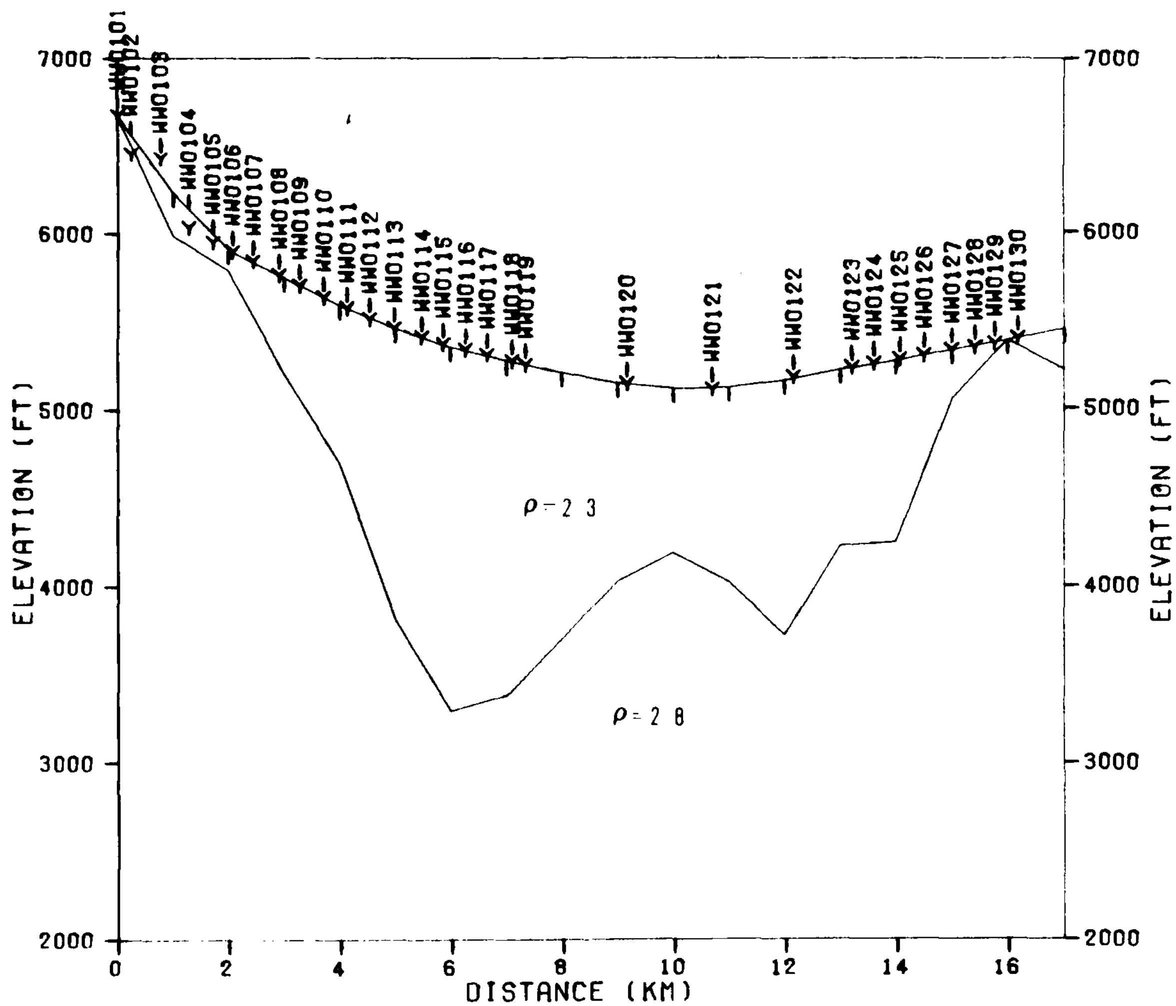
MM0108
MM0109
MM0110



HORIZONTAL SCALE 0 5 10 15 20 25 30 KILOFEET; 0 2 4 6 8 10 KILOMETERS

VERTICAL SCALE 0 200 400 600 800 1000 METERS; 0 1000 2000 3000 FEET

EXPLANATION

TOP CBA (Y) & REGIONAL ( )

MIDDLE RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL ( )

BOTTOM ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS ( )

INTERPRETED GRAVITY
WHIRLWIND VALLEY

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DEPARTMENT OF THE AIR FORCE

FUGRO NATIO

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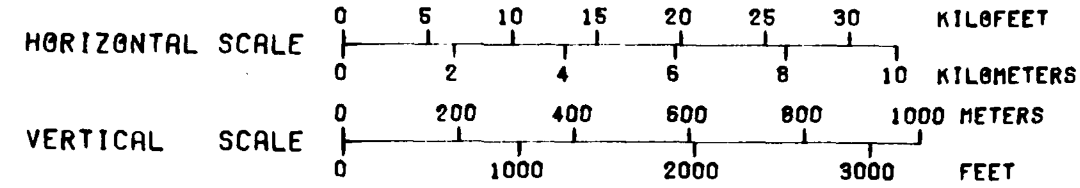

EXPLANATION

TOP CBA (Y) & REGIONAL ( )

MIDDLE RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL ( )

BOTTOM ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS ( )
MODEL OF BEDROCK SURFACE ( )

DENSITY VALUES (ρ=2 3) g/cm³

DISTANCE SCALE 1:125,000

INTERPRETED GRAVITY PROFILE WW-1
WHIRLWIND VALLEY, UTAH

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FIGURE 4

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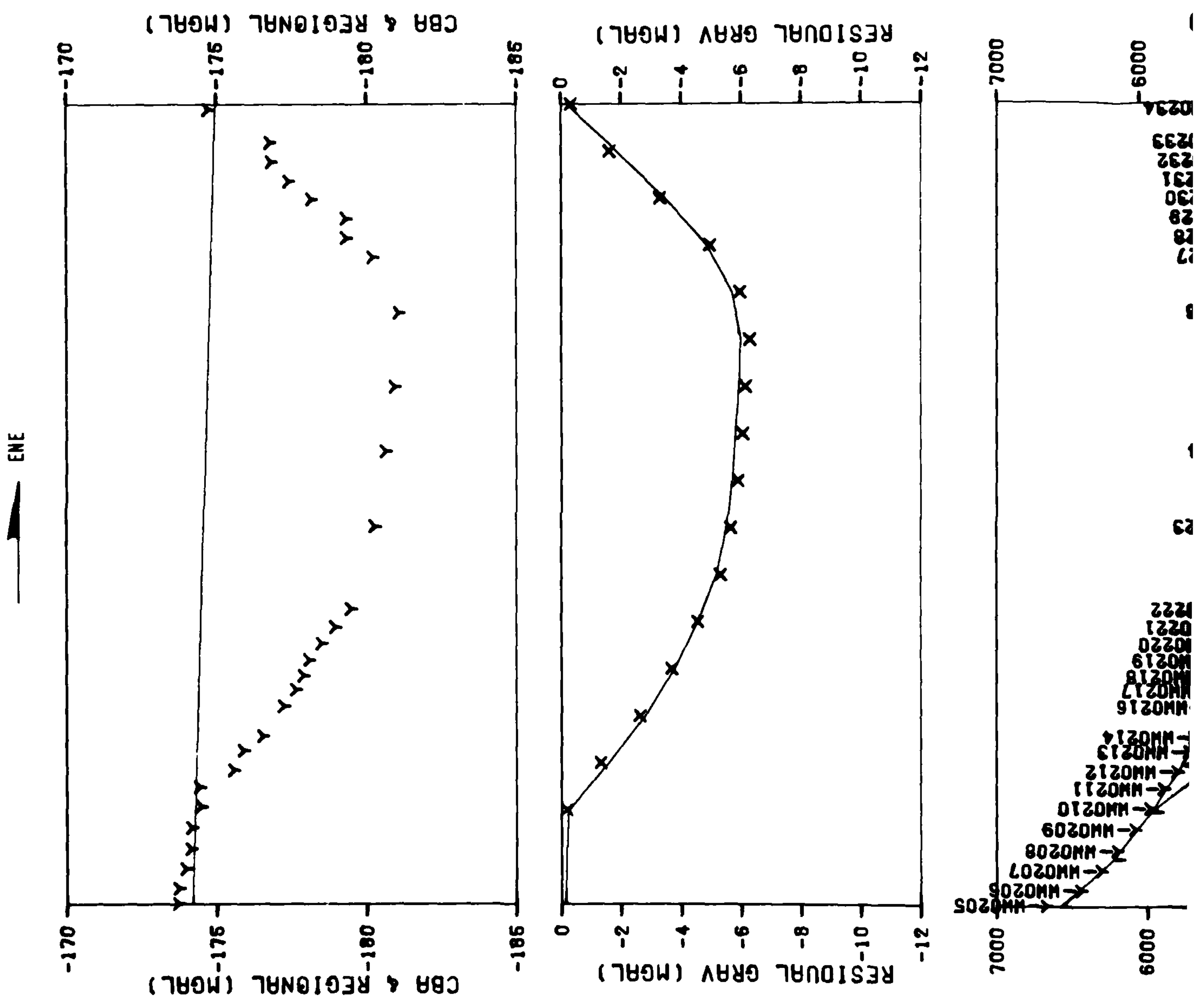
CBA & REGIONAL (MGAL)
-170
-175
-180
-185
RESIDUAL GRAV (MGAL)
0
-2
-4
-6
-8
-10
-12
7000
6000
ENE
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MM0206
MM0207
MM0208
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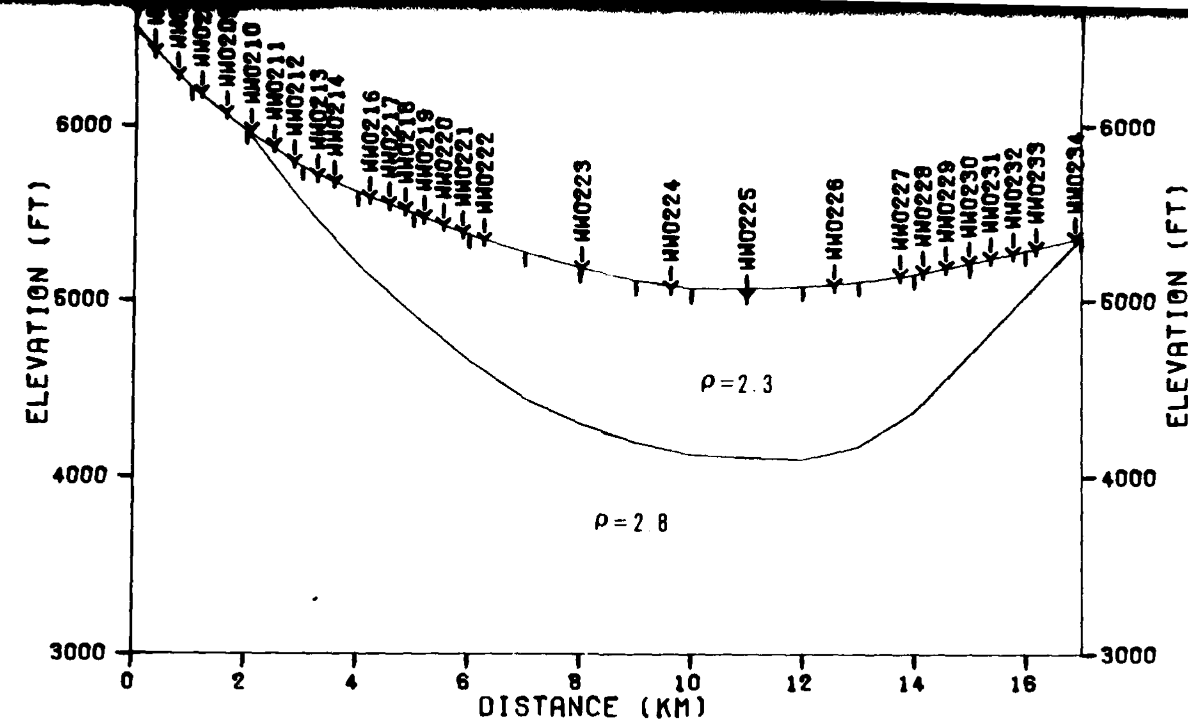

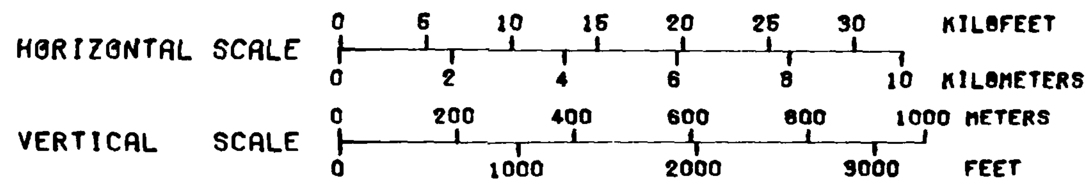

EXPLANATION

TOP CBA (Y) & REGIONAL ( )

MIDDLE RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL ( )

BOTTOM ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS ( )
MODEL OF BEDROCK SURFACE ( )

DENSITY VALUES (ρ=2.3) g/cm^3

DISTANCE SCALE 1:125,000

INTERPRETED GRAVITY PROFILE WW-2 WHIRLWIND VALLEY, UTAH	
MX SITING INVESTIGATION DEPARTMENT OF THE AIR FORCE - BMO	FIGURE 5

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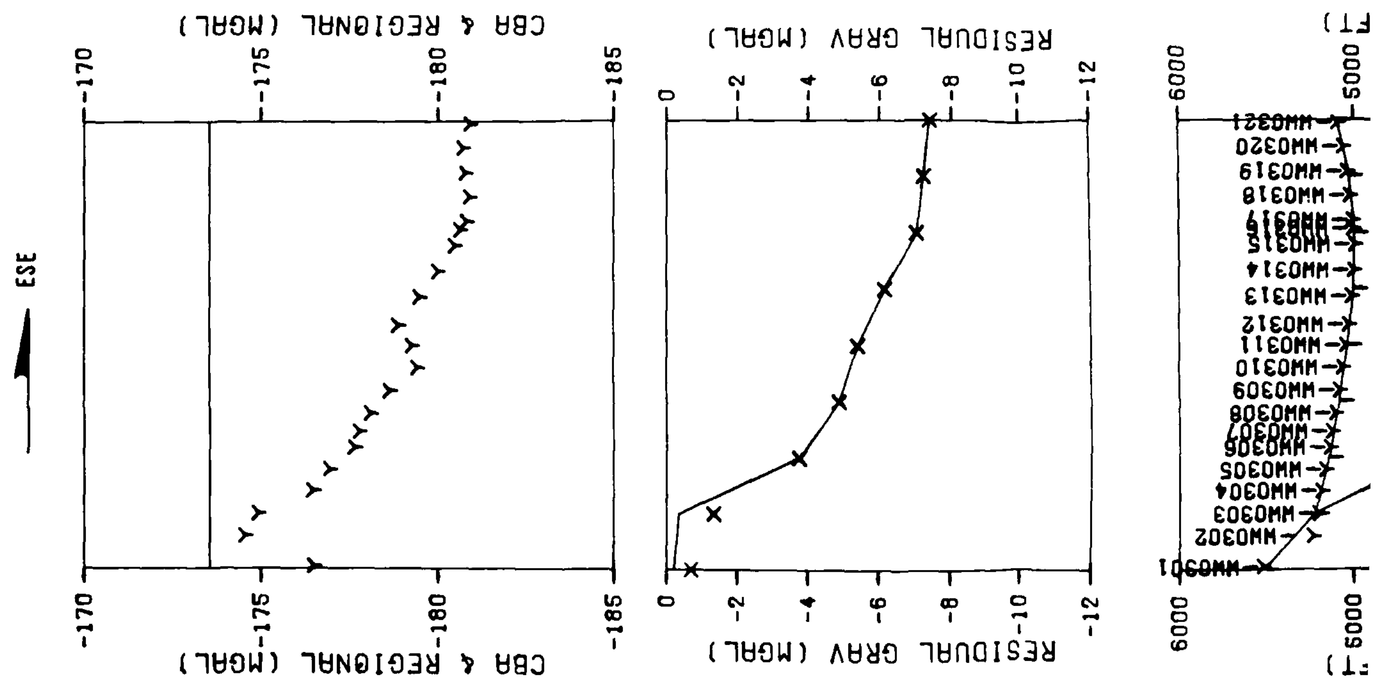
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-175
-180
-185
RESIDUAL GRAV (MGAL)
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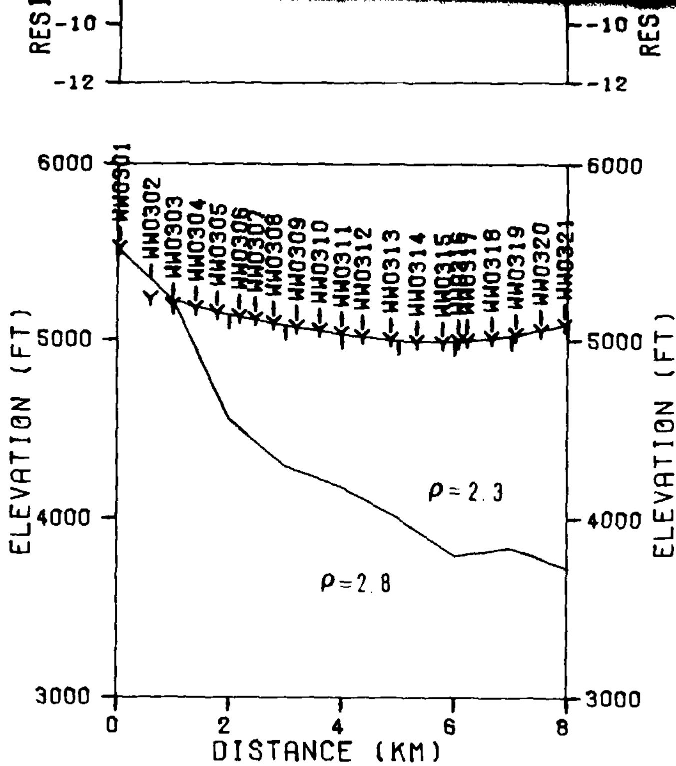

HORIZONTAL SCALE 0 5 10 KILOFEET; 0 2 4 KILOMETERS

VERTICAL SCALE 0 200 400 METERS; 0 1000 FEET

EXPLANATION

TOP — CBA (Y) & REGIONAL (——)

MIDDLE — RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL (——)

BOTTOM — ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS (——)
MODEL OF BEDROCK SURFACE (——)

DENSITY VALUES ($\rho = 2.3$) g/cm^3

DISTANCE SCALE 1:125,000

INTERPRETED GRAVITY PROFILE WW-3 WHIRLWIND VALLEY, UTAH	
MX SITING INVESTIGATION DEPARTMENT OF THE AIR FORCE - BMO	FIGURE 6

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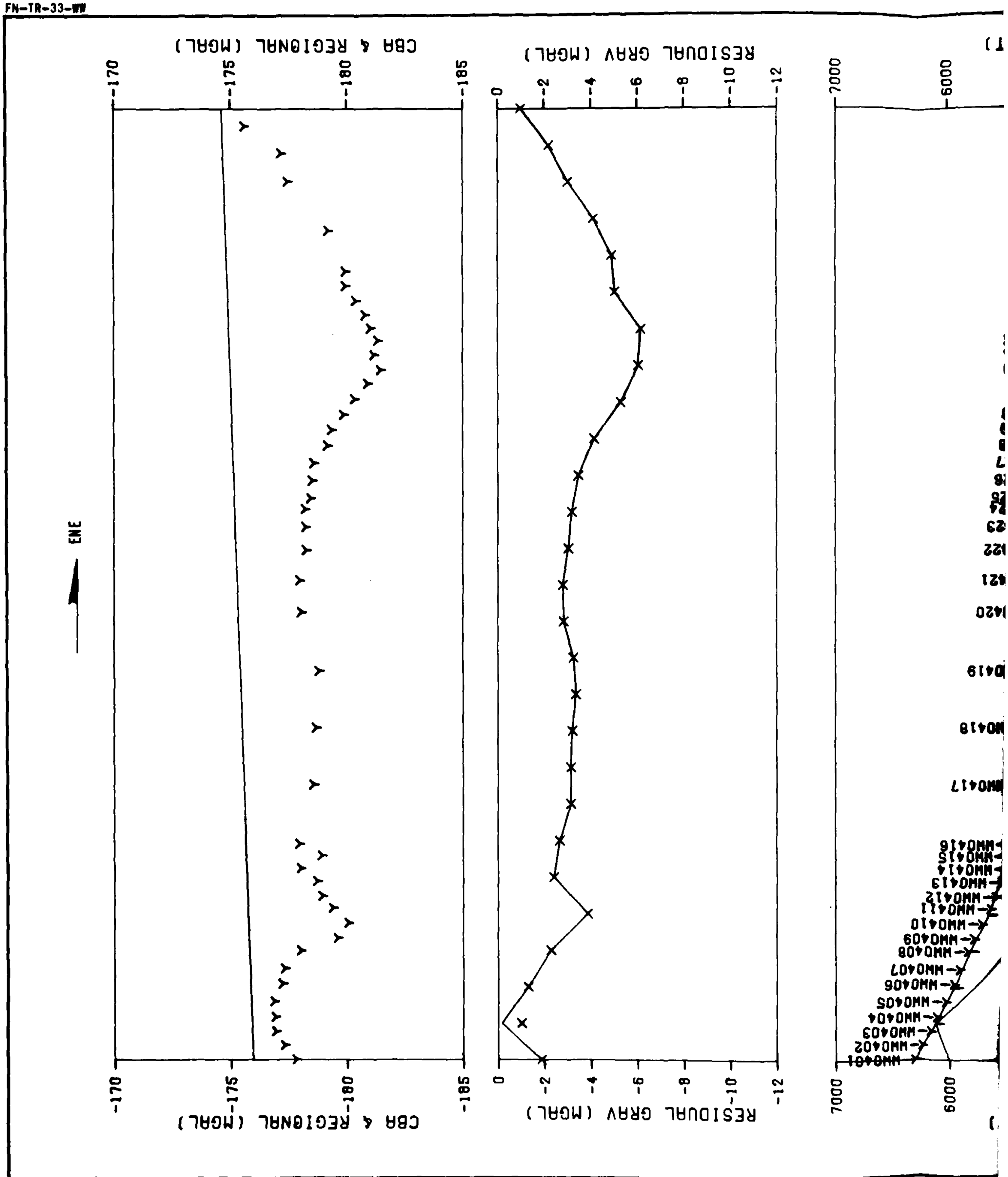
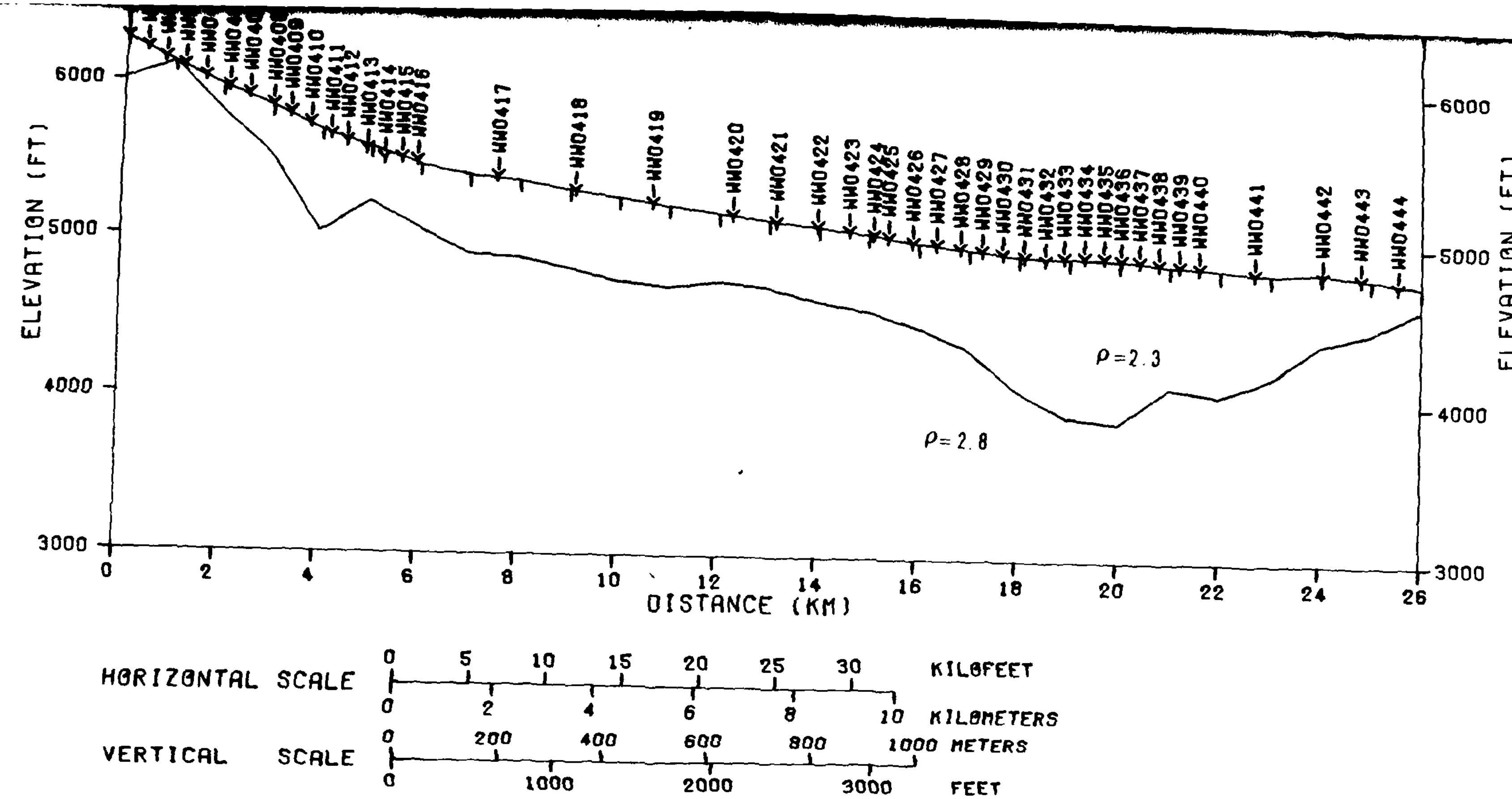
2 1


ENE
CBA & REGIONAL (MGAL)
RESIDUAL GRAV (MGAL)
MM0401
MM0402
MM0403
MM0404
MM0405
MM0406
MM0407
MM0408
MM0409
MM0410
MM0411
MM0412
MM0413
MM0414
MM0415
MM0416



EXPLANATION

TOP — CBA (Y) & REGIONAL ( )

MIDDLE — RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL ( )

BOTTOM — ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS ( )
MODEL OF BEDROCK SURFACE ( )
DENSITY VALUES ($\rho = 2.3$) g/cm^3
DISTANCE SCALE 1:125,000

INTERPRETED GRAVITY PROFILE WW-4 WHIRLWIND VALLEY, UTAH	
MX SITING INVESTIGATION DEPARTMENT OF THE AIR FORCE · BMO	FIGURE 7

FUGRO NATIONAL, INC.

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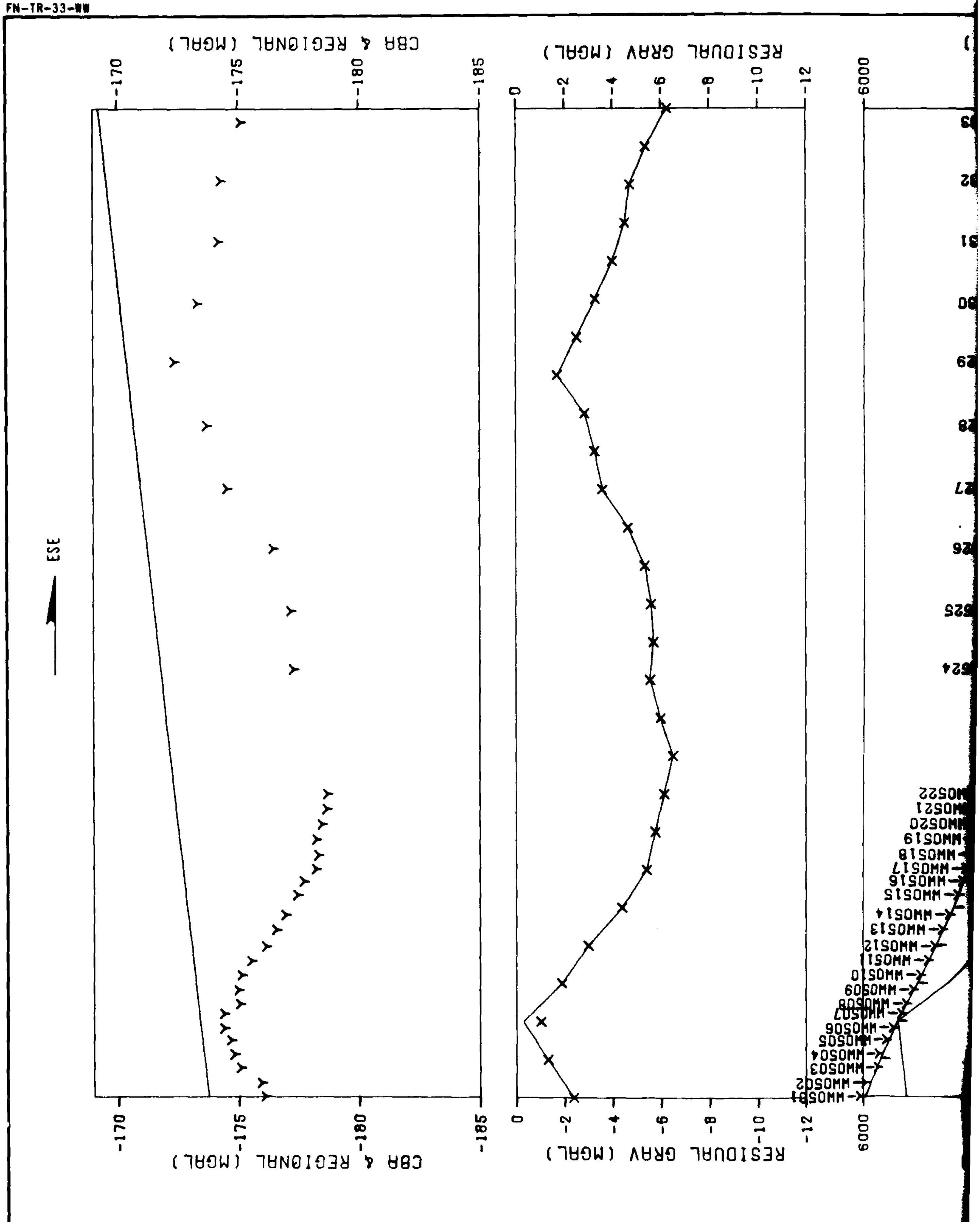
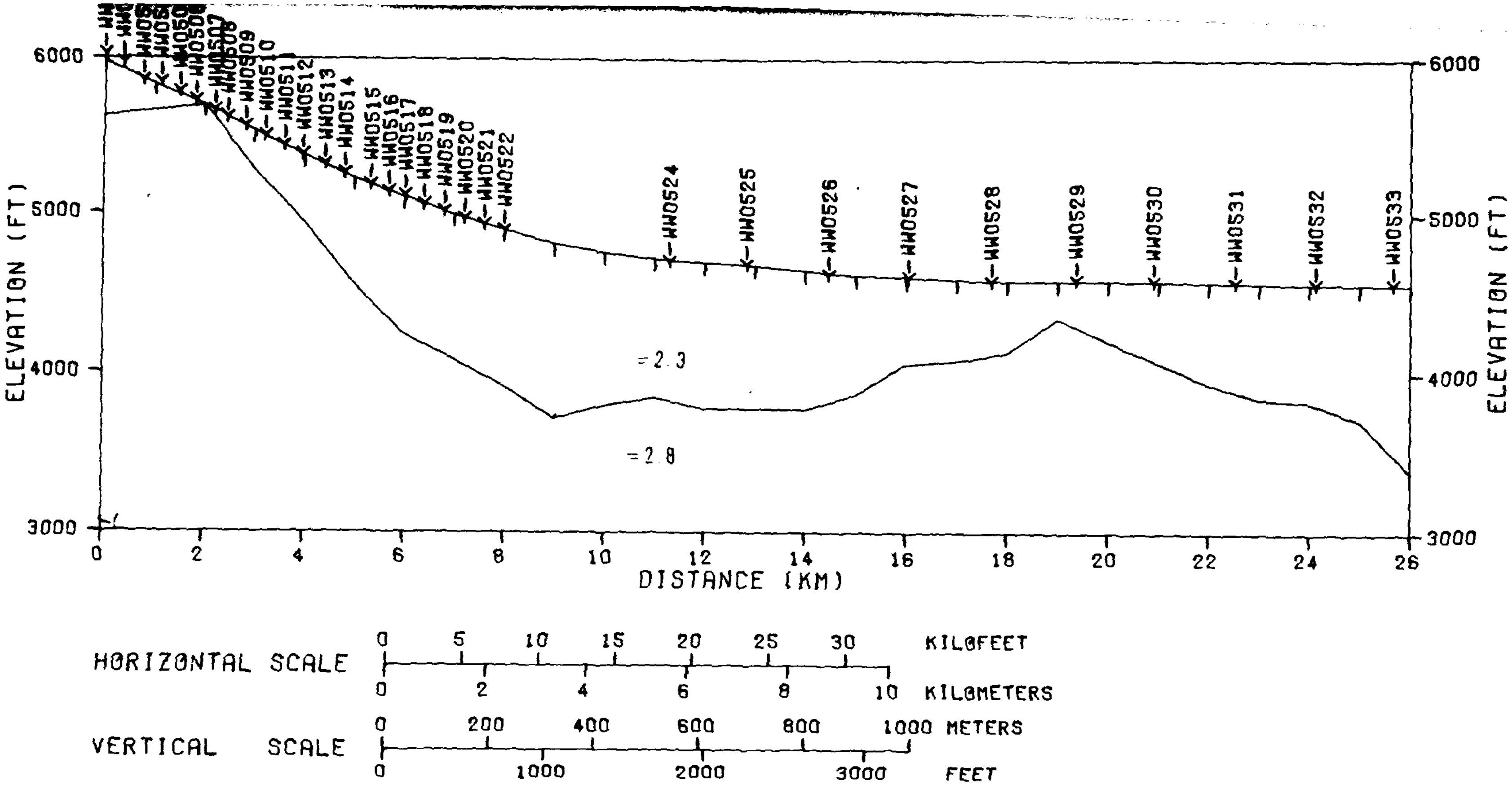

CBA & REGIONAL (MGAL)
-170
-175
-180
-185
RESIDUAL GRAV (MGAL)
0
-2
-4
-6
-8
-10
-12
6000
ESE
MMOS01
MMOS02
MMOS03
MMOS04
MMOS05
MMOS06
MMOS07
MMOS08
MMOS09
MMOS10
MMOS11
MMOS12
MMOS13
MMOS14
MMOS15
MMOS16
MMOS17
MMOS18
MMOS19
MMOS20
MMOS21
MMOS22



EXPLANATION

TOP CBA (Y) & REGIONAL ( )

MIDDLE RESIDUAL GRAV: OBSERVED VALUES (INTERPOLATED) (X)
CALCULATED FROM MODEL ( )

BOTTOM ELEVATION: STATION ELEVATIONS (Y) & IDENTIFICATION (WW0112)
INTERPOLATED SURFACE ELEVATIONS ( )
MODEL OF BEDROCK SURFACE ( )
DENSITY VALUES (ρ = 2.3) g/cm^3
DISTANCE SCALE 1:125,000

INTERPRETED GRAVITY PROFILE WW-5
WHIRLWIND VALLEY, UTAH

MX SITING INVESTIGATION
DEPARTMENT OF THE AIR FORCE BMO

FIGURE 8

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5.0 CONCLUSIONS

Whirlwind Valley is interpreted to be a relatively shallow structural valley. It has the long, narrow shape typically created by range bounding faults in the Basin and Range Physiographic province.

However, if such faults do exist in Whirlwind Valley, they must be relatively small because, they are not visible at the surface and are not clearly defined by the gravity profiles.

The interpretations of the two profiles (3 and 4) near Red Knolls and Long Ridge suggest that these topographic features are not basin boundaries and they represent no obstacle to ground-water movement between Whirlwind Valley and Sevier Desert. However, the high at the end of Profile 4 and at 19 km on Profile 5 (Figure 8) may be evidence of a bedrock high just east of Long Ridge and Red Knolls. This suggested feature could restrict ground-water migration except for very shallow aquifers.

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APPENDIX A1.0

GENERAL PRINCIPLES OF THE GRAVITY EXPLORATION METHOD

A1.0 GENERAL PRINCIPLES OF THE GRAVITY EXPLORATION METHOD

A1.1 GENERAL

A gravity survey involves measurement of differences in the gravitational field between various points on the earth's surface. The gravitational field values being measured are the same as those influencing all objects on the surface of the earth. They are generally associated with the force which causes a 1 gm mass to be accelerated at 980 cm/sec^2. This force is normally referred to as a 1 g force.

Even though in many applications the gravitational field at the earth's surface is assumed to be constant, small but distinguishable differences in gravity occur from point to point. In a gravity survey, the variations are measured in terms of milligals. A milligal is equal to 0.001 cm/second^2 or 0.00000102 g. The differences in gravity are caused by geometrical effects, such as differences in elevation and latitude, and by lateral variations in density within the earth. The lateral density variations are a result of changes in geologic conditions. For measurements at the surface of the earth, the largest factor influencing the pull of gravity is the density of all materials between the center of the earth and the point of measurement.

To detect changes produced by differing geological conditions, it is necessary to detect differences in the gravitational field as small as a few milligals. To recognize changes due to

geological conditions, the measurements are "corrected" to account for changes due to differences in elevation and latitude.

Given this background, the basic concept of the gravitational exploration method, the anomaly, can be introduced. If, instead of being an oblate spheroid characterized by complex density variations, the earth were made up of concentric, homogeneous shells, the gravitational field would be the same at all points on the surface of the earth. The complexities in the earth's shape and material distribution are the reason that the pull of gravity is not the same from place to place. A difference in gravity between two points which is not caused by the effects of known geometrical differences, such as in elevation, latitude, and surrounding terrain, is referred to as an "anomaly."

An anomaly reflects lateral differences in material densities. The gravitational attraction is smaller at a place underlain by relatively low density material than it is at a place underlain by a relatively high density material. The term "negative gravity anomaly" describes a situation in which the pull of gravity within a prescribed area is small compared to the area surrounding it. Low-density alluvial deposits in basins such as those in the Nevada-Utah region produce negative gravity anomalies in relation to the gravity values in the surrounding mountains which are formed by more dense rocks.

The objective of gravity exploration is to deduce the variations in geologic conditions that produce the gravity anomalies identified during a gravity survey.

A1.2 INSTRUMENTS

The sensing element of a LaCoste and Romberg gravimeter is a mass suspended by a zero-length spring. Deflections of the mass from a null position are proportional to changes in gravitational attraction. These instruments are sealed and compensated for atmospheric pressure changes. They are maintained at a constant temperature by an internal heater element and thermostat. The absolute value of gravity is not measured directly by a gravimeter. It measures relative values of gravity between one point and the next. Gravitational differences as small as 0.01 milligal can be measured.

A1.3 FIELD PROCEDURES

The gravimeter readings were calibrated in terms of absolute gravity by taking readings twice daily at nearby USGS gravity base stations. Gravimeter readings fluctuate because of small time-related deviations due to the effect of earth tides and instrument drift. Field readings were corrected to account for these deviations. The magnitude of the tidal correction was calculated using an equation suggested by Goguel (1954):

$$C = P + N\cos\phi\,(\cos\phi + \sin\phi) + S\cos\phi\,(\cos\phi - \sin\phi)$$

where C is the tidal correction factor, P, N, and S are time-related variables, and ϕ is the latitude of the observation point. Tables giving the values of P, N, and S are published annually by the European Association of Exploration Geophysicists.

The meter drift correction was based on readings taken at a designated base station at the start and end of each day. Any difference between these two readings after they were corrected for tidal effects was considered to have been the result of instrumental drift. It was assumed that this drift occurred at a uniform rate between the two readings. Corrections for drift were typically only a few hundredths of a milligal. Readings corrected for tidal effects and instrumental drift represented the observed gravity at each station. The observed gravity values represent the total gravitational pull of the entire earth at the measurement stations.

A1.4 DATA REDUCTION

Several corrections or reductions are made to the observed gravity to isolate the portion of the gravitational pull which is due to the crustal and near-surface materials. The gravity remaining after these reductions is called the "Bouguer Anomaly." Bouguer Anomaly values are the basis for geologic interpretation. To obtain the Bouguer Anomaly, the observed gravity is adjusted to the value it would have had if it had been measured at the geoid, a theoretically defined surface which approximates the surface of mean sea level. The difference between the "adjusted" observed gravity and the gravity at the geoid calculated for a theoretically homogeneous earth is the Bouguer Anomaly.

Four separate reductions, to account for four geometrical effects, are made to the observed gravity at each station to arrive at its Bouguer Anomaly value.

a. Free-Air Effect: Gravitational attraction varies inversely as the square of the distance from the center of the earth. Thus corrections must be applied for elevation. Observed gravity levels are corrected for elevation using the normal vertical gradient of:

$$FA = -0.09406 \text{ mg/ft } (-0.3086 \text{ milligals/meter})$$

where FA is the free-air effect (the rate of change of gravity with distance from the center of the earth). The free-air correction is positive in sign since the correction is opposite the effect.

b. Bouguer Effect: Like the free-air effect, the Bouguer effect is a function of the elevation of the station, but it considers the influence of a slab of earth materials between the observation point on the surface of the earth and the corresponding point on the geoid (sea level). Normal practice, which is to assume that the density of the slab is 2.67 grams per cubic centimeter was followed in these studies. The Bouguer correction (B_c), which is opposite in sign to the free-air correction, was defined according to the following formula.

$$B_c = 0.01276\ (2.67)\ h_f \text{ (milligals per foot)}$$

$$B_c = 0.04185\ (2.67)\ h_m \text{ (milligals per meter)}$$

where h_f is the height above sea level in feet and h_m is the height in meters.

c. Latitude Effect: Points at different latitudes will have different "gravities" for two reasons. The earth (and the geoid) is spheroidal, or flattened at the poles. Since points at higher latitudes are closer to the center of the earth than points near the equator, the gravity at the higher latitudes is larger. As the earth spins, the centrifugal acceleration causes a slight decrease in gravity. At the higher latitudes where the earth's radii are smaller, the centrifugal acceleration diminishes. The gravity formula for the Geodetic Reference System, 1967, gives the theoretical value of gravity at the geoid as a function of latitude. It is:

$$g = 978.0381\ (1 + 0.0053204 \sin^2 \phi - 0.0000058 \sin^2 2\phi) \text{ gals}$$

where g is the theoretical acceleration of gravity and ϕ is the latitude in degrees. The positive term accounts for the spheroidal shape of the earth. The negative term adjusts for the centrifugal acceleration.

The previous two corrections (free air and Bouguer) have adjusted the observed gravity to the value it would have had at the geoid (sea level). The theoretical value at the geoid for the latitude of the station is then subtracted from the adjusted observed gravity. The remainder is called the Simple Bouguer Anomaly (SBA). Most of this gravity represents the effect of material beneath the station, but part of it may be due to irregularities in terrain (upper part of the Bouguer slab) away from the station.

d. Terrain Effect: Topographic relief around the station has a negative effect on the gravitational force at the station. A nearby hill has upward gravitational pull and a nearby valley contributes less downward attraction than a nearby material would have. Therefore, the corrections are always positive. Corrections are made to the SBA when the terrain effects were 0.1 milligal or larger. Terrain corrected Bouguer values are called the Complete Bouguer Anomaly (CBA). When the CBA is obtained, the reduction of gravity at individual measurement points (stations) is complete.

A1.5 INTERPRETATION

The first step in interpretation is to separate the portion of the CBA that might be caused by the lightweight, basin-fill material overlying the heavier bedrock material which forms the surrounding mountains and presumably the basin floor. Since the valley-fill sediments are absent at the stations read in the mountains, the CBA values at these bedrock stations are used as the basis for constructing a regional field over the valley. A regional field is an estimation of the values the CBA would have had if the light weight sediments (the anomaly) had not been there.

The difference between the CBA and the regional field is called the "residual" field or residual anomaly. The residual field is the interpreter's estimation of the gravitational effect of the geologic anomaly. The zero value of the residual anomaly is not exactly at the rock outcrop line but at some

distance on the "rock" side of the contact. The reason for this is found in the explanation of the terrain effect. There is a component of gravitational attraction from material which is not directly beneath a point.

If the "regional" is well chosen, the magnitude of the residual anomaly is a function of the thickness of the anomalous (fill) material and the density contrast. The density contrast is the difference in density between the alluvial and bedrock material. If this contrast were known, an accurate calculation of the thickness could be made. In most cases, the densities are not well known and they also vary within the study area. In these cases, it is necessary to use typical densities for materials similar to those in the study area.

If the selected average density contrast is smaller than the actual density contrast, the computed depth to bedrock will be greater than the actual depth and vice-versa. The computed depth is inversely proportional to the density contrast. A ten percent error in density contrast produces a ten percent error in computed depth. An iterative computer program is used to calculate a subsurface model which will yield a gravitational field to match (approximately) the residual gravity anomaly.

APPENDIX A2.0

LISTS OF GRAVITY DATA

PROFILE #1
WHIRLWIND VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM / OBSV GRAV / THEO GRAV	FAA	CBA +1000
WW0101	392811	1131828	6671S	1	681437508	81792154204212170	4816	82748
WW0102	392830	1131819	6452S	8	412437544	81803155719212198	4246	82659
WW0103	392847	1131788	6428S	14	371437577	81846155759212223	4034	82495
WW0104	392870	1131761	6032S	3	287437621	81883158443212258	2959	82674
WW0105	392882	1131735	5947S	1	266437645	81920159055212275	2746	82731
WW0106	392893	1131714	5895Y	0	237437667	81949159370212291	2561	82691
WW0107	392893	1131685	5841Y	0	221437666	81990159657212291	2339	82637
WW0108	392898	1131653	5761Y	0	197437679	82036159972212299	1696	82442
WW0109	392905	1131629	5701Y	0	187437694	82070160274212309	1615	82358
WW0110	392909	1131599	5634Y	0	170437703	82112160002212316	1305	82260
WW0111	392915	1131571	5572Y	0	157437716	82152160864212324	980	82132
WW0112	392919	1131542	5510Y	0	149437725	82193161137212330	664	82019
WW0113	392923	1131512	5455Y	0	136437734	82236161348212336	350	81882
WW0114	392931	1131479	5404Y	0	122437751	82283161575212346	85	81775
WW0115	392939	1131454	5364Y	0	119437767	82318161806212359	-78	81748
WW0116	392948	1131428	5331Y	0	111437785	82355162022212373	-181	81748
WW0117	392956	1131403	5300Y	0	106437802	82390162233212385	-275	81754
WW0118	392965	1131374	5268Y	0	102437820	82431162470212398	-354	81781
WW0119	392983	1131364	5246Y	0	96437854	82444162692212425	-369	81844
WW0120	393052	1131260	5136S	0	79437988	82587163810212527	-383	82179
WW0121	393052	1131147	5105S	0	74437995	82749164042212527	-443	82220
WW0122	393053	1131040	5174Y	0	73438003	82903163511212528	-330	82096
WW0123	393071	113 971	5226Y	0	77438041	83000163379212555	5	82258
WW0124	393077	113 944	5249Y	0	79438053	83038163275212564	109	82285
WW0125	393084	113 913	5274Y	0	80438068	83082163139212574	199	82290
WW0126	393090	113 884	5295Y	0	84438081	83123163175212583	419	82445
WW0127	393102	113 853	5325Y	0	85438105	83167163247212601	758	82681
WW0128	393109	113 826	5342Y	0	89438120	83205163228212611	689	82756
WW0129	393127	113 808	53[illegible]2Y	0	91438154	832291631782126[illegible]	1003	82605
WW0130	393143	113 785	5392Y	0	95438185	83261162967212662	1046	82752

END OF LIST

PROFILE #2
WHIRLWIND VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
WW0205	392450	1131656	6663S	1	522436850	82066153754211637	4829	82626
WW0206	392450	1131628	6434S	9	536436852	82106155104211637	4021	82622
WW0207	392454	1131599	6300S	1	502436861	82147155939211642	3584	82601
WW0208	392464	1131573	6193Y	0	426436881	82184156052211657	3279	82583
WW0209	392475	1131544	6074Y	0	361436903	82225157441211673	2937	82580
WW0210	392481	1131514	5974Y	0	317436916	82267158055211682	2616	82550
WW0211	392491	1131488	5862Y	0	285436936	82304158673211697	2329	82554
WW0212	392508	1131468	5793Y	0	253436969	82331159150211722	1947	82442
WW0213	392519	1131442	5714Y	0	227436991	82368159632211738	1666	82407
WW0214	392525	1131422	5676Y	0	215437003	82396159621211748	1486	82344
WW0216	392542	1131383	5588Y	0	185437037	82451160331211773	1147	82273
WW0217	392553	1131361	5552Y	0	174437059	82481160534211789	994	82232
WW0218	392566	1131345	5521Y	0	163437084	82503160725211806	675	82208
WW0219	392576	1131324	5478Y	0	155437103	82533160988211823	716	82186
WW0220	392584	1131302	5434Y	0	147437119	82564161225211834	534	82146
WW0221	392596	1131281	5392Y	0	138437143	82593161461211852	556	82102
WW0222	392607	1131257	5350Y	0	131437165	82626161683211869	167	82049
WW0223	392618	1131134	5193Y	0	107437193	82802162588211885	-424	81970
WW0223	392618	1131134	5193Y	0	107437193	82802162588211885	-424	81970
WW0224	392632	1131023	5085Y	0	89437225	82960163242211905	-813	81933
WW0225	392646	113 930	5033Y	0	79437257	83093163550211927	-1011	81902
WW0226	392669	113 824	5091Y	0	74437306	83243163231211960	-623	81688
WW0227	392684	113 744	5145Y	0	78437339	83356163010211983	-554	81976
WW0228	392693	113 717	5163Y	0	80437357	83394163000211996	-408	82063
WW0229	392698	113 690	5169Y	0	81437366	83433162851212003	-320	82063
WW0230	392705	113 662	5215Y	0	84437382	83472162619212013	-116	82180
WW0231	392710	113 636	5242Y	0	84437393	83509162736212021	51	82255
WW0232	392716	113 609	5267Y	0	90437406	83548162653212030	166	82314
WW0233	392723	113 581	5296Y	0	91437421	83587162489212040	291	82318
WW0234	392734	113 534	5350Y	0	102437444	83654162373212056	669	82523
WW0235	392734	113 534	5350Y	0	94437444	836541621 8212056	484	82236

END OF LIST

PROFILE #3
WHIRLWIND VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
WW0301	391997	1131152	5512Y	1	159436042	82625160080210967	987	82347
WW0302	391995	113111252251T		0	156436041	82882162000210964	206	82543
WW0303	391986	1131087	5190S	0	133436026	82919162180210951	74	82504
WW0304	391970	1131061	5176Y	0	120436009	82957162111210936	-115	82351
WW0305	391975	1131034	5150Y	0	113436009	82996162224210934	-245	82303
WW0306	391971	1131007	5128Y	0	104436003	83035162290210928	-384	82232
WW0307	391967	113 988	5113Y	0	101435997	83063162363210923	-444	82219
WW0308	391963	113 960	5093Y	0	93435991	83095162451210916	-535	82187
WW0309	391958	113 938	5070Y	0	87435985	83135162538210909	-603	82133
WW0310	391953	113 911	5052Y	0	84435976	83175162557210902	-798	82054
WW0311	391946	113 884	5035Y	0	79435966	83214162677210895	-836	82071
WW0312	391944	113 858	5017Y	0	77435962	83251162619210888	-856	82109
WW0313	391934	113 826	5001Y	0	73435946	83298162646210873	-966	82049
WW0314	391924	113 796	4988Y	0	70435929	83342162656210859	-1061	81996
WW0315	391912	113 768	4982Y	0	67435909	83383162830210841	-1125	81949
WW0316	391903	113 751	4991Y	0	66435893	83408162749210826	-1179	81934
WW0317	391899	113 742	4994Y	0	65435886	83422162706210822	-1114	81916
WW0318	391891	113 713	5012Y	0	63435873	83464162585210810	-1061	81906
WW0319	391888	113 683	5028Y	0	63435869	83507162495210805	-995	81919
WW0320	391882	113 654	5048Y	0	64435860	83550162369210797	-926	81926
WW0321	391877	113 625	5081Y	0	70435853	83592162138210790	-635	81905

END OF LIST

PROFILE #4
WHIRLWIND VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
WW0401	391313	1131923	6295Y	1	280434731	81768154118209956	3404	82210
WW0402	391320	1131897	6225Y	1	258434745	81805154615209966	3238	82264
WW0403	391331	1131873	6154Y	0	260434767	81839155098209983	3032	82303
WW0404	391335	1131846	6103Y	0	230434776	81877155439209989	2692	82305
WW0405	391341	1131818	6029Y	0	213434789	81917155920209998	2060	82311
WW0406	391353	1131787	5964Y	0	202434813	81961156299210016	2412	82273
WW0407	391373	1131763	5916Y	0	188434651	81994156622210045	2254	82264
WW0408	391380	1131731	5846Y	0	177434866	82040156995210055	1956	82195
WW0409	391388	1131708	5792Y	0	169434882	82072157179210067	1021	82036
WW0410	391402	1131682	5728Y	0	162434910	82108157546210088	1363	81989
WW0411	391422	1131658	5652Y	0	149434948	82141158110210117	1184	82056
WW0412	391437	1131640	5604Y	0	141434977	82166158474210140	1074	82102
WW0413	391452	1131616	5554Y	0	139435026	82200158819210162	931	82125
WW0414	391465	1131594	5495Y	0	137435031	82230159267210181	601	82195
WW0415	391475	1131572	5498Y	0	131435051	82261159177210195	727	82104
WW0416	391492	1131554	5488Y	0	130435084	82286159378210221	767	82199
WW0417	391504	1131442	5388Y	0	111435113	82406159938210238	404	82139
WW0418	391523	113133752999T		0	101435154	82596160492210260	104	82126
WW0419	391543	113123252280T		0	94435197	82745160948210296	-148	82115
WW0420	391565	1131123	5154Y	0	86435245	82900161512210329	-317	82192
WW0421	391577	1131065	5117Y	0	80435270	82983161763210346	-430	82196
WW0422	391586	1131008	5090Y	0	77435291	83064161914210359	-549	82169
WW0423	391596	113 960	5064Y	0	73435312	83124162088210374	-631	82171
WW0424	391614	113 936	5041Y	0	73435347	83165162254210401	-705	82174
WW0425	391621	113 917	5030Y	0	71435361	83192162309210411	-765	82150
WW0426	391626	113 884	5001Y	0	69435372	83239162488210419	-868	82144
WW0427	391632	113 852	4988Y	0	67435385	83285162571210427	-920	82136
WW0428	391636	113 819	4966Y	0	66435395	83332162649210434	-1049	82076
WW0429	391642	113 790	4952Y	0	64435406	83375162762210442	-1114	82060
WW0430	391650	113 763	4937Y	0	63435424	83411162780210454	-1214	82010
WW0431	391659	113 735	4918Y	0	62435442	83451162863210467	-1326	81963
WW0432	391664	113 706	4901Y	0	62435453	83492162913210475	-1441	81905
WW0433	391668	113 681	4921Y	0	60435462	83528162743210480	-1425	81850
WW0434	391670	113 653	4923Y	0	59435468	83568162762210484	-1390	81677
WW0435	391670	113 625	4921Y	0	58435470	93008162765210484	-1415	81862
WW0436	391673	113 602	4910Y	0	57435477	83041162066210486	-1418	81893
WW0437	391675	113 577	4903Y	0	57435482	83077162932210491	-1416	81917
WW0438	391677	113 549	4887Y	0	56435487	83717163075210494	-1431	81957
WW0439	391679	113 521	4874Y	0	56435493	83757163199210497	-1450	82002
WW0440	391681	113 494	4863Y	0	55435498	83795163267210500	-1467	82001
WW0441	391686	113 416	4836Y	0	57435512	83907163507210507	-1488	82074
WW0442	391692	113 325	4817Y	0	52435529	84041163811210516	-1572	82249
WW0443	391698	113 270	4809Y	0	51435534	84116163897210525	-1572	82277
WW0444	391709	113 183	4765U	0	51435569	84241164337210541	-1363	82436

END OF LIST

PROFILE #5
WHIRLWIND VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG	MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
WW0501	39	851	1131840	6024Y	1	272433881	81923155241209274	2060	82367
WW0502	39	855	1131814	5972Y	4	266433890	81960155577209280	2500	82402
WW0503	39	857	1131787	5852Y	0	273433895	81999156384209284	2173	82486
WW0504	39	859	1131761	5841Y	1	253433900	82036156499209286	2180	82514
WW0505	39	860	1131735	5776Y	0	243433904	82073156917209288	1985	82529
WW0506	39	864	1131712	5718Y	0	236433912	82106157303209294	1818	82556
WW0507	39	870	1131685	5648Y	0	233433925	82145157735209302	1587	82556
WW0508	39	870	1131667	5606Y	0	206433926	82170157952209302	1405	82492
WWA509	39	868	1131642	5548Y	0	184433924	82207158325209299	1234	82497
WW0510	39	865	1131615	5490Y	0	173433920	82246158064209295	1037	82485
WW0511	39	861	1131588	5425Y	0	158433914	82285159024209289	789	82444
WW0512	39	862	1131562	5369Y	0	152433916	82322159306209291	544	82383
WW0513	39	862	1131532	5308Y	0	141433919	82366159639209291	303	82339
WW0514	39	858	1131505	5251Y	0	133433914	82405159946209285	76	82302
WW0515	39	857	1131469	5179Y	0	122433914	82457160336209284	-204	82252
WW0516	39	854	1131444	5137Y	0	116433910	82493160566209279	-371	82224
WW0517	39	837	1131423	5114Y	0	119433880	82525160622209254	-500	82175
WW0518	39	828	1131398	5057Y	0	111433864	82561160953209241	-700	82164
WW0519	39	825	1131370	5013Y	0	121433861	82602161206209236	-650	82172
WW0520	39	821	1131343	4966Y	0	107433855	82641161475209230	-1019	82150
WW0521	39	820	1131315	4928Y	0	101433855	82682161693209229	-1161	82130
WW0522	39	814	1131288	4892Y	0	101433845	82721161893209220	-1288	82127
WW0523	39	807	1131172	5063Y	0	126433839	82889162787209209	1223	84082
WW0524	39	791	1131061	4695Y	0	81433816	83050163206209186	-1002	82267
WW0525	39	786	113 955	4677Y	0	64433813	83203163332209179	-1635	82278
WW0526	39	767	113 844	4613Y	0	58433795	83364163768209151	-1973	82352
WW0527	39	765	113 734	4600Y	0	54433784	83523160035209145	-1621	82543
WW0528	39	743	113 622	4573Y	0	53433754	83086160252209115	-1631	82620
WW0529	39	744	113 505	4585U	0	50433754	83555164319209116	-1651	82761
WW0530	39	746	113 398	4578U	0	53433774	84009164263209120	-1775	82664
WW0531	39	767	113 285	4569U	0	51433783	84172164234209121	-1696	82577
WW0532	39	748	113 173	4564U	0	46433792	84333164260209123	-1913	82567
WW0533	39	769	113 63	4562Y	0	44433836	84490164221209153	-1999	82484
WW0534	39	779	113 10	4558Y	0	43433659	84566164198209160	-2076	82420

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